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Appendix A

Inventory and Characteristics of Spent Nuclear Fuel, High-Level Radioactive Waste, and Other Materials

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APPENDIX A. INVENTORY AND CHARACTERISTICS OF SPENT NUCLEAR FUEL, HIGH-LEVEL RADIOACTIVE WASTE, AND OTHER MATERIALS

A.1 Introduction

This appendix describes the inventory and characteristics of the spent nuclear fuel and high-level radioactive waste that the U.S. Department of Energy (DOE) anticipates it would place in a monitored geologic repository at Yucca Mountain. It includes information about other highly radioactive material that DOE could dispose of in the proposed repository. It also provides information on the background and sources of the material, present storage conditions, the final disposal forms, and the amounts and characteristics of the material. The data provided in this appendix are the best available estimates of projected inventories.

The Proposed Action inventory evaluated in this environmental impact statement (EIS) consists of 70,000 metric tons of heavy metal (MTHM), comprised of 63,000 MTHM of commercial spent nuclear fuel and 7,000 MTHM of DOE materials. The DOE materials consist of 2,333 MTHM of spent nuclear fuel and 8,315 canisters (4,667 MTHM) of solidified high-level radioactive waste. The inventory includes approximately 50 metric tons (55 tons) of surplus weapons-usable plutonium as spent mixed-oxide fuel and immobilized plutonium.

The Nuclear Waste Policy Act, as amended (also called the NWPA), prohibits the U.S. Nuclear Regulatory Commission from approving the emplacement of more than 70,000 MTHM in the first repository until a second repository is in operation [Section 114(d)]. However, in addition to the Proposed Action, this EIS evaluates the cumulative impacts for two additional inventories (referred to as Inventory Modules 1 and 2):

- The Module 1 inventory consists of the Proposed Action inventory plus the remainder of the total projected inventory of commercial spent nuclear fuel, high-level radioactive waste, and DOE spent nuclear fuel. Emplacement of Inventory Module 1 wastes in the repository would raise the total amount emplaced above 70,000 MTHM. As mentioned above, emplacement of more than 70,000 MTHM of spent nuclear fuel and high-level radioactive waste would require legislative action by Congress unless a second licensed repository was in operation.

- Inventory Module 2 includes the Module 1 inventory plus the inventories of the candidate materials, commercial Greater-Than-Class-C low-level radioactive waste and DOE Special-Performance-Assessment-Required waste. There are several reasons to evaluate the potential for disposing of these candidate materials in a monitored geologic repository in the near future. Because both materials exceed Class C low-level radioactive limits for specific radionuclide concentrations as defined in 10 CFR Part 61, they are generally unsuitable for near-surface disposal. Also, the Nuclear Regulatory Commission specifies in 10 CFR 61.55(a)(2)(iv) the disposal of Greater-Than-Class-C waste in a repository unless the Commission approved disposal elsewhere. Further, during the scoping process for this EIS, several commenters requested that DOE evaluate the disposal of other radioactive waste types that might require isolation in a repository. Disposal of Greater-Than-Class-C and Special-Performance-Assessment-Required wastes at the proposed Yucca Mountain Repository could require a determination by the Nuclear Regulatory Commission that these wastes require permanent isolation. In addition, the present 70,000-MTHM limit on waste at the Yucca Mountain Repository could have to be addressed either by legislation or by opening a second licensed repository.

A.1.1 INVENTORY DATA SUMMARY

There are six general inventory categories, as follows:

- Commercial spent nuclear fuel
- DOE spent nuclear fuel
- High-level radioactive waste
- Surplus weapons-usable plutonium
- Commercial Greater-Than-Class-C waste
- DOE Special-Performance-Assessment-Required waste

This section summarizes the detailed inventory data in Section A.2. The data provide a basis for the impact analysis in this EIS. Data are provided for the candidate materials included in the initial 70,000 MTHM for the Proposed Action and other inventory that is not currently proposed but might be considered for repository disposal in the foreseeable future.

This summary provides general descriptive and historic information about each waste type, including the following:

- Primary purpose and use of the data
- General comparison of the data between waste types
- Potential for change in inventory data

Table A-1 lists the inventory data that DOE used in the EIS analyses and their descriptions throughout the document.

A.1.1.1 Sources

Figure A-1 shows the locations of generators or sources of spent nuclear fuel and high-level radioactive waste. Spent nuclear fuel is fuel that has been withdrawn from a nuclear reactor following irradiation. The Proposed Action includes the disposal of 63,000 MTHM of commercial spent nuclear fuel in the repository. More than 99 percent of the commercial spent nuclear fuel would come from commercial nuclear reactor sites in 33 states (DOE 1995a, all). In addition, DOE manages an inventory of spent nuclear fuel. The Proposed Action includes 2,333 MTHM of spent nuclear fuel from four DOE locations: the Savannah River Site in South Carolina, the Hanford Site in Washington, the Idaho National Engineering and Environmental Laboratory, and Fort St. Vrain in Colorado.

High-level radioactive waste is the highly radioactive material resulting from the reprocessing or treatment of spent nuclear fuel. The Proposed Action includes disposing of 8,315 canisters of high-level radioactive waste in the repository. High-level radioactive waste is stored at the Savannah River Site, the Hanford Site, the Idaho National Engineering and Environmental Laboratory, and the West Valley Demonstration Project in New York.

The President has declared approximately 50 metric tons (55 tons) of plutonium to be surplus to national security needs (DOE 1998a, page 1-1). This surplus weapons-usable plutonium includes purified plutonium, nuclear weapons components, and plutonium residues. This inventory is included in the Proposed Action, and the Department would dispose of it as either spent mixed oxide fuel from a commercial nuclear reactor (that is, commercial spent nuclear fuel) or immobilized plutonium in a high-level radioactive waste canister (that is, as high-level radioactive waste), or a combination of these two inventory categories (DOE 1998a, page 1-3). Spent mixed-oxide fuel would come from one or more of

Table A-1. Use of Appendix A radioactivity inventory data in EIS chapters and appendixes (page 1 of 2).

Item[a]	Appendix A	EIS section
Number of commercial nuclear sites	Table A-3	1.1, 2.2, 2.2.2, 2.4.1, 2.4.2.3, 2.4.2.4, 2.4.2.8, 2.4.3, 6.1, 7.0, 7.2.1, 7.3, J.1.3.1.1
Number of DOE sites	A.1.1	1.1, 2.2, 2.2.2, 2.4.1, 2.4.2.3, 2.4.2.4, 2.4.2.8, 2.4.3, 6.1, 7.0, 7.2.1, 7.3
Mapped location of sites	Figure A-1	Figure 1-1, Several Chapter 6, 7, App. J and K figures
Commercial SNF material	A.2.1.5.3	1.1.1
Commercial SNF dimensions	Table A-15	1.1.1, Figure 1-3, H.2.1.4
Commercial SNF cladding material	A.2.1.5.3	1.1.2.1.1, 5.2.2, K.2.1.4.1
Percentage of commercial SNF with stainless-steel cladding	A.2.1.5.3	1.1.2.1.1, 1.5.3, 5.2.2, 5.5.1, K.2.1.4.1
MOX SNF part of commercial SNF Proposed Action	A.2.4.5.1.1	1.1.2.1.1
Number of sites with existing or planned ISFSIs	Table A-4	1.1.2.1.1
Amount of commercial SNF projected for each site	Tables A-6 and A-7	1.1.2.1.1, 6.1.1, K.2.1.6
List of commercial SNF sites, state, operations period	Table A-3	Table 1-1
DOE SNF storage locations	Table A-17	1.1.2.1.2, K.2.1.6
HLW includes immobilized Pu	A.2.4.5.2.1	1.1.2.2
HLW generators	A.2.3.2	1.1.2.2, K.2.1.6
HLW vitrification status	A.2.3.4	1.1.2.2
Weapons-usable Pu declared surplus	A.2.4.1	1.1.2.3
Two forms: MOX and immobilized Pu	A.2.4.1	1.1.2.3
Proposed Action inventory	A.1	1.1.2.5, 1.3.2, 1.6.3.1, 2.1, Figure 2-3, 2.1.4, 2.2.2, 2.2.3, 5.1, 5.2.2, 5.6.3, 6.1.1.1, 7.0, 7.2, 8.1.2.1, J.1.3.1.1, J.1.3.1.2, K.2.1.6
Total projected inventory commercial SNF	Figure A-2	1.1.2.5, 1.6.3.1, 7.2, 7.3, 8.1.2.1, J.1.3.1.1, K.2.1.6
Total projected inventory DOE SNF	Figure A-2	1.1.2.5, 1.6.3.1, 6.1.1.1, 7.2, 7.3, 8.1.2.1, J.1.3.1.2, K.2.1.6
Total projected inventory HLW	Figure A-2	1.1.2.5, 1.6.3.1, 7.2, 7.3, 8.1.2.1, K.2.1.6
Total projected GTCC waste	Table A-51	1.6.3.1, 7.3, 8.1.2.1, I.3.1.2.4, J.1.3.1.3
Total projected SPAR waste	Table A-56	1.6.3.1, 7.3, 8.1.2.1, I.3.1.2.4, J.1.3.1.3
HLW canister dimensions	A.2.3.5.6	Figure 2-3
Thermal generation of 1 MTHM of commercial SNF at time of emplacement	Table A-14	2.1.1.2
Commercial SNF, DOE SNF, and immobilized Pu contain fissile material	A.2.1.5.2 A.2.2.5.2 A.2.4.5.2.2	2.1.2.2.2
Kr-85 (gas) is contained in fuel gap of commercial SNF	A.2.1.5.2	4.1, 4.1.2.3.2
Typical radionuclide inventory for commercial SNF	Tables A-8 and A-9	4.1.8.1, 6.1.3.2.1, H.2.1.4, Table H-4, I.3.1.1, I.3.1.2.1, J.1.5.2.1, K.2.1.6

Table A-1. Use of Appendix A radioactivity inventory data in EIS chapters and appendixes (page 2 of 2).

Item[a]	Appendix A	EIS section
Amount of chromium per SNF assembly	A.2.1.5.3	5.1.2
Commercial SNF comprises at least 92% of radioactivity in Proposed Action	A.1.1.4.2	5.2.2, 5.2.3.3
DOE SNF has a variety of cladding	A.2.2.5.3	5.2.2
Commercial SNF has higher radionuclide content than DOE SNF or HLW	Table A-2	6.1.2.1
Cs-137, actinide, and total curies contained in a rail shipping cask for commercial SNF, HLW, DOE SNF, and naval fuel	Derived from Tables A-8, A-27, and A-18	Table 6-2, Table J-17
Radiological inventory of GTCC and SPAR waste much less than commercial SNF or HLW	Derived from Tables A-8, A-27, A-18, A-54, and Section A.2.6.4	8.2.7, 8.2.8, 8.4.1.1, F.3
Average radionuclide inventory per package for SPAR and GTCC waste	Derived from Table A-54 and Section A.2.6.4	8.3.1.1, Table I-9
C-14 (gas) is contained in fuel gap of commercial SNF	Tables A-8 and A-9	5.5, 8.3.1.1, I.3.3, I.7
Typical PWR burnup, initial enrichment, and average cooling time	A.2.1.5	G.2.3.2, H.2.1.4, J.1.4.2.5
Typical BWR burnup, initial enrichment, and average cooling time	A.2.1.5	G.2.3.2, H.2.1.4
N-reactor radionuclide inventory per canister is larger than HLW radionuclide per canister.	Tables A-18 and A-27	H.2.1.1
21 PWR assemblies contain a higher radionuclide content than 44 BWR assemblies	Tables A-8 and A-9	H.2.1.1
DOE would emplace twice as many PWR assemblies as BWR	A.2.1.5.1	H.2.1.1
N-reactor fuel represents a large quantity of DOE SNF	Table A-17	H.2.1.1
Mass of N-reactor fuel per canister	Table A-17	H.2.1.1
Immobilized Pu disk dimensions	A.2.4.5.2.1	I.3
Number of immobilized Pu cans per HLW canister	A.2.4.5.2.1	I.3
DOE SNF radionuclide inventory	Table A-18	I.3.1.1, I.3.1.2.1
Assumed packaging method for GTCC and SPAR	A.2.5.4, A.2.6.4	I.3.1.2.4
Chemical makeup of waste inventory	Tables A-12, -13, -19, -29, -30, -31, -32, -33, and -34	Table I-10
MTU per assembly for PWR and BWR	Table A-15	J.1.4.1.1
Most HLW stored in underground vaults	A.2.3.3	K.2.1.5.2

a. Abbreviations: SNF = spent nuclear fuel; MOX = mixed oxide; ISFSI = independent spent fuel storage installation; HLW = high-level radioactive waste; Pu = plutonium; GTCC = Greater-Than-Class-C; SPAR = Special-Performance-Assessment-Required; MTHM = metric tons of heavy metal; Kr = krypton; Cs = cesium; PWR = pressurized-water reactor; BWR = boiling-water reactor; MTU = metric tons of uranium.

the existing commercial reactor sites. Although the location of the plutonium immobilization facility has not been decided, DOE (1998a, page 1-9) has identified the Savannah River Site as the preferred alternative. For purposes of analysis, this EIS assumes that the high-level radioactive waste canisters, which would contain immobilized plutonium and borosilicate glass, would come from the Savannah River Site.

Figure A-1. Locations of commercial and DOE sites and Yucca Mountain.

Greater-Than-Class-C waste is waste with concentrations of certain radionuclides that exceed the Class C limits stated in 10 CFR Part 61, thereby making it unsuitable for near-surface disposal. Greater-Than-Class-C waste is generated by a number of sources including commercial nuclear utilities, sealed radioactive sources, and wastes from "other generators." These other generators include carbon-14 users, industrial research and development applications, fuel fabricators, university reactors, and others. These wastes are currently stored at the commercial and DOE sites and exist in most states. They are included in Inventory Module 2 of the EIS but are not part of the Proposed Action.

Special-Performance-Assessment-Required wastes are also Greater-Than-Class-C wastes managed by DOE and are stored primarily at the Hanford Site, Idaho National Engineering and Environmental Laboratory, West Valley Demonstration Project, and Oak Ridge National Laboratory in Tennessee. These wastes are included in Inventory Module 2 of the EIS but are not part of the Proposed Action.

A.1.1.2 Present Storage and Generation Status

Commercial spent nuclear fuel is stored at reactor sites in either a spent fuel pool or in a dry storage configuration generally referred to as an independent spent fuel storage installation. Through 1995, approximately 32,000 MTHM of commercial spent nuclear fuel has been discharged from reactors (Heath 1998, Appendix C). DOE spent nuclear fuel is also stored either underwater in basins or in a dry storage configuration similar to that used for commercial spent nuclear fuel.

As discussed in the next section, DOE would receive high-level radioactive waste at the repository in a solidified form in stainless-steel canisters. Until shipment to the repository, the canisters would be stored at the commercial and DOE sites. With the exception of the West Valley Demonstration Project, the filled canisters would be stored in below-grade facilities. The West Valley canisters would be stored in an above-ground shielded facility.

A.1.1.3 Final Waste Form

Other than drying or potential repackaging, processing is not necessary for commercial spent nuclear fuel. Therefore, the final form would be spent nuclear fuel either as bare intact assemblies or in sealed canisters. Bare intact fuel assemblies are those that do not have any disruption of their cladding and could be shipped to the repository in an approved shipping container for repackaging in a waste package in the Waste Handling Building. Other assemblies would be shipped to the repository in canisters that were either intended or not intended for disposal. Canisters not intended for disposal would be opened and repackaged in waste packages in the Waste Handling Building.

For most of the DOE spent nuclear fuel categories, the fuel would be shipped in disposable canisters (canisters that can be shipped and are suitable for direct insertion into waste packages without being opened) in casks licensed by the Nuclear Regulatory Commission. Uranium oxide fuels with intact zirconium alloy cladding are similar to commercial spent nuclear fuel and could be shipped either in DOE standard canisters or as bare intact assemblies. Uranium metal fuels from Hanford and aluminum-based fuels from the Savannah River Site could require additional treatment or conditioning before shipment to the repository. If treatment was required, these fuels would be packaged in DOE disposable canisters. Category 14 sodium-bonded fuels are also expected to require treatment before disposal.

High-level radioactive waste shipped to the repository would be in stainless-steel canisters. The waste would have undergone a solidification process that yielded a leach-resistant material, typically a glass form called borosilicate glass. In this process, the high-level radioactive waste is mixed with glass-forming materials, heated and converted to a durable glass waste form, and poured into stainless-steel canisters (Picha 1997, Attachment 4, page 2). Depending on future decisions stemming from other EISs, ceramic and metal waste matrices could be sent to the repository from Argonne National Laboratory-West

in Idaho. The ceramic and metal matrices would be different solidified mixtures that also would be in stainless-steel canisters. These wastes would be the result of the proposed electrometallurgical treatment of sodium bonded fuels.

As briefly described in Section A.1.1.1, the surplus weapon-usable plutonium would probably be sent to the repository in two different waste forms—spent mixed-oxide fuel assemblies or an immobilized plutonium ceramic form in a high-level radioactive waste canister and surrounded by high-level radioactive waste. The spent mixed-oxide fuel assemblies would be very similar to conventional low-enriched uranium assemblies and DOE would treat them as such. The immobilized plutonium would be placed in small cans, inserted in the high-level radioactive waste canisters, and covered with molten borosilicate glass (can-in-canister technique). The canisters containing immobilized plutonium and high-level radioactive waste would be externally identical to the normal high-level radioactive waste canisters.

A.1.1.4 Waste Characteristics

A.1.1.4.1 *Mass and Volume*

As discussed in Section A.1, the Proposed Action includes 70,000 MTHM in the forms of commercial spent nuclear fuel, DOE spent nuclear fuel, high-level radioactive waste, and surplus weapons-usable plutonium. Figure A-2 shows percentages of MTHM included in the Proposed Action and the relative amounts of the totals of the individual waste types included in the Proposed Action. As stated above, the remaining portion of the wastes is included in Inventory Module 1. Because Greater-Than-Class-C and Special-Performance-Assessment-Required wastes are measured in terms of volume, Figure A-3 shows the relative volume of the wastes in Inventory Module 2 compared to the inventory in Module 1.

The No-Action Alternative (see Chapter 7 and Appendix K) used this information to estimate the mass and volume of the spent nuclear fuel and high-level radioactive waste at commercial and DOE sites in five regions of the contiguous United States.

The mass and volume data for commercial spent nuclear fuel is the result of several years of annual tracking and projections by DOE, which anticipates few changes in the overall mass and volume projections for this waste type. The data projections for DOE spent nuclear fuel are fairly stable because most of the projected inventory already exists, as opposed to having a large amount projected for future generation. Mass and volume data for high-level radioactive waste estimates are not as reliable. Most high-level radioactive waste currently exists as a form other than solidified borosilicate glass. The solidification processes at the Savannah River Site and West Valley Demonstration Project are under way; therefore, the resulting mass and volume are known. However, the processes at the Idaho National Engineering and Environmental Laboratory and the Hanford Site have not started. Therefore, there is some uncertainty about the mass and volume that would result from those processing operations. For this analysis, DOE assumed that the high-level radioactive waste from the Hanford Site and the Idaho National Engineering and Environmental Laboratory would represent 65 and 6 percent of the total high-level radioactive waste inventory, respectively, in terms of the number of canisters.

A.1.1.4.2 *Amount and Nature of Radioactivity*

The primary purpose of presenting these data is to quantify the isotopic inventory expected in the projected waste types. These data were used for accident scenario analyses associated with transportation, handling, and repository operations. The data were also used to develop the source term associated with accident scenarios and long-term effects for the Proposed Action and the No-Action Alternative.

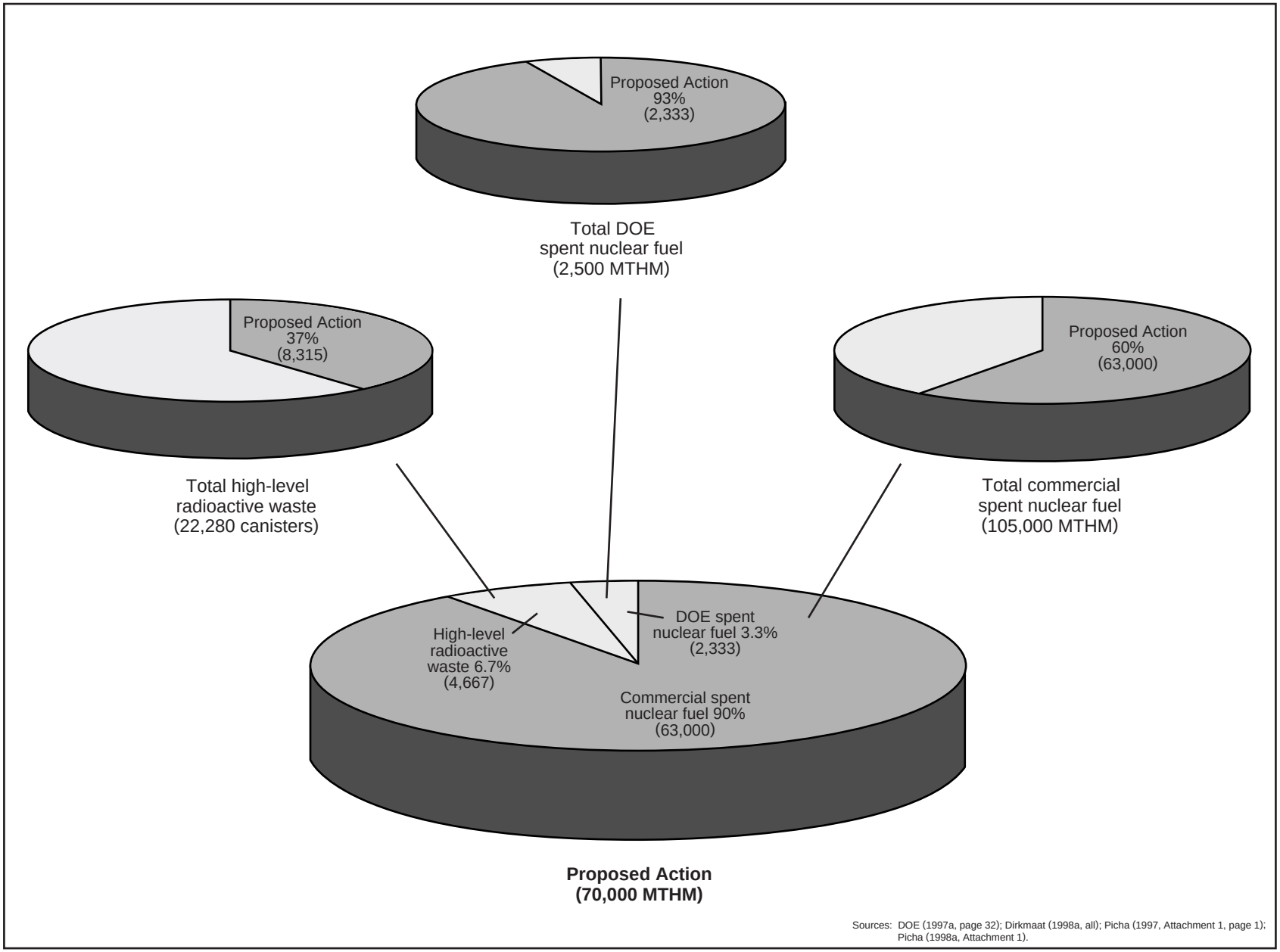


Figure A-2. Proposed Action spent nuclear fuel and high-level radioactive waste inventory.

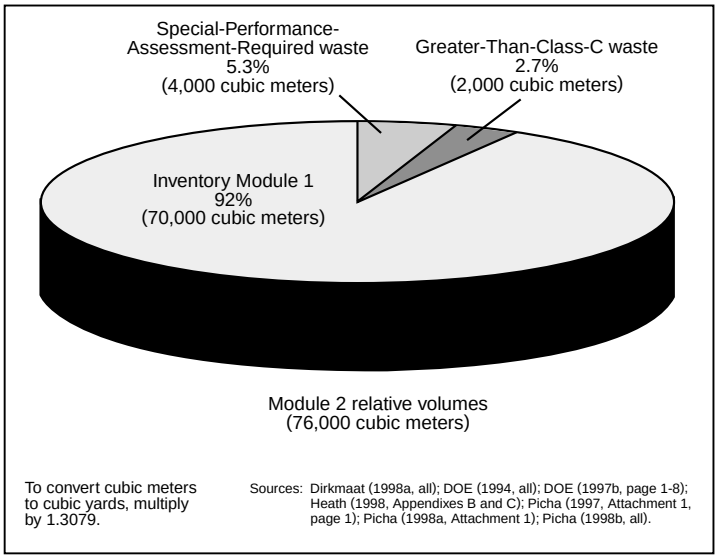


Figure A-3. Inventory Module 2 volume.

In a comparison of the relative amounts of radioactivity in a particular waste type, radionuclides of concern depend on the analysis being performed. For example, cesium-137 is the primary radionuclide of concern when reviewing preclosure impacts and shielding requirements. For postclosure impacts, the repository performance assessment evaluated nine radionuclides (see Appendix I) and identified technetium-99 and neptunium-237 as the nuclides that provide the greatest impacts. Plutonium-238 and -239 are shown in Chapter 7 to contribute the most to doses for the No-Action Alternative. Table A-2 presents the inventory of each of these radionuclides included in the Proposed Action. Figure A-4 shows that at least 92 percent of the total inventory of each of these radionuclides is in commercial spent nuclear fuel.

Table A-2. Selected nuclide inventory for the Proposed Action (curies).

	Commercial spent nuclear fuel	DOE spent nuclear fuel	High-level radioactive waste	Surplus plutonium	Totals
Cesium-137	4.0×10^{9}	1.7×10^{8}	1.7×10^{8}	NA[a]	4.3×10^{9}
Technetium-99	9.2×10^{5}	2.9×10^{4}	2.1×10^{4}	NA	9.7×10^{5}
Neptunium-237	2.8×10^{4}	1.1×10^{3}	4.5×10^{2}	NA	3.0×10^{4}
Plutonium-238	2.1×10^{8}	5.6×10^{6}	3.0×10^{6}	7.6×10^{4}	2.2×10^{8}
Plutonium -239	2.3×10^{7}	3.8×10^{5}	4.4×10^{4}	1.0×10^{6}	2.5×10^{7}

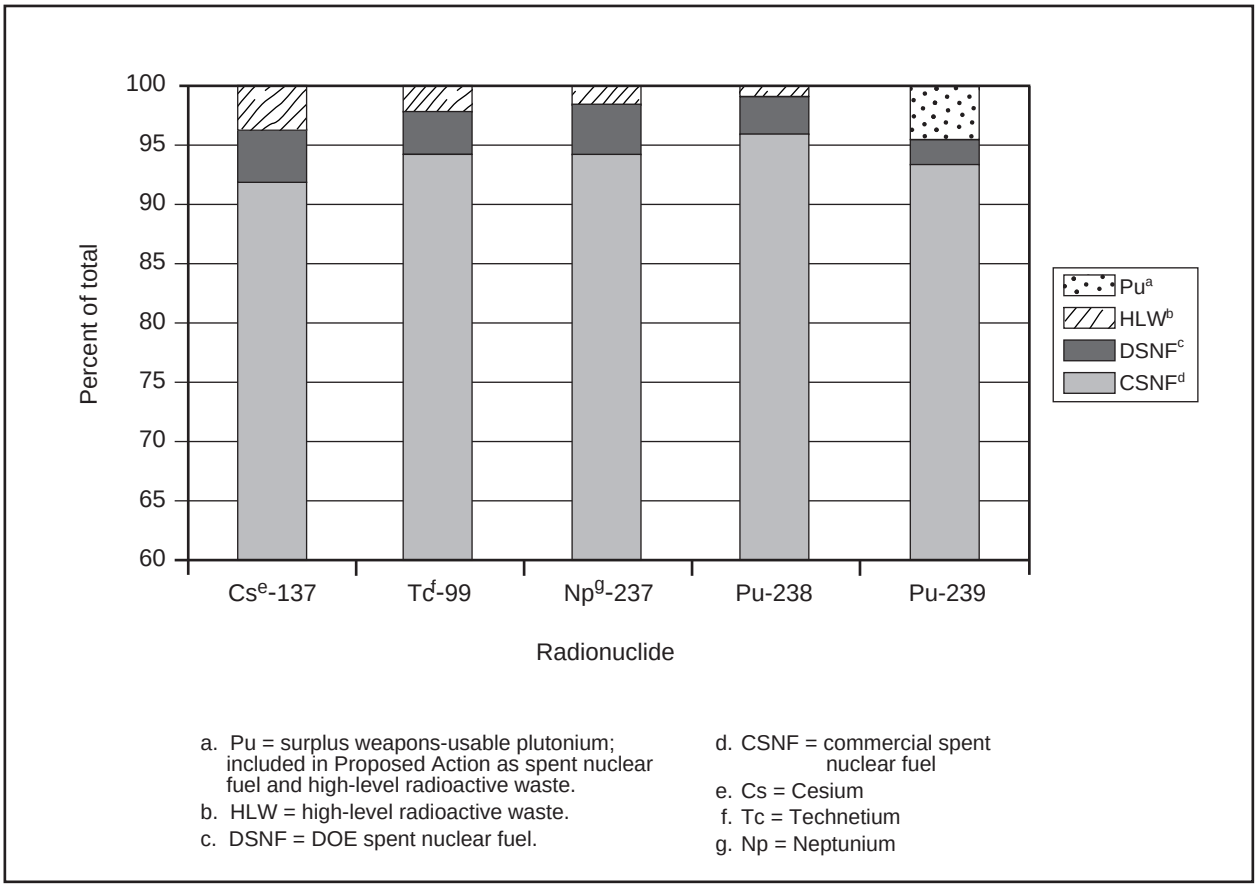
a. NA = not applicable.

A.1.1.4.3 *Chemical Composition*

The appendix presents data for the chemical composition of the primary waste types. For commercial spent nuclear fuel, the elemental composition of typical pressurized-water and boiling-water reactor fuel is provided on a per-assembly basis. Data are also provided on the number of stainless-steel clad assemblies in the current inventory.

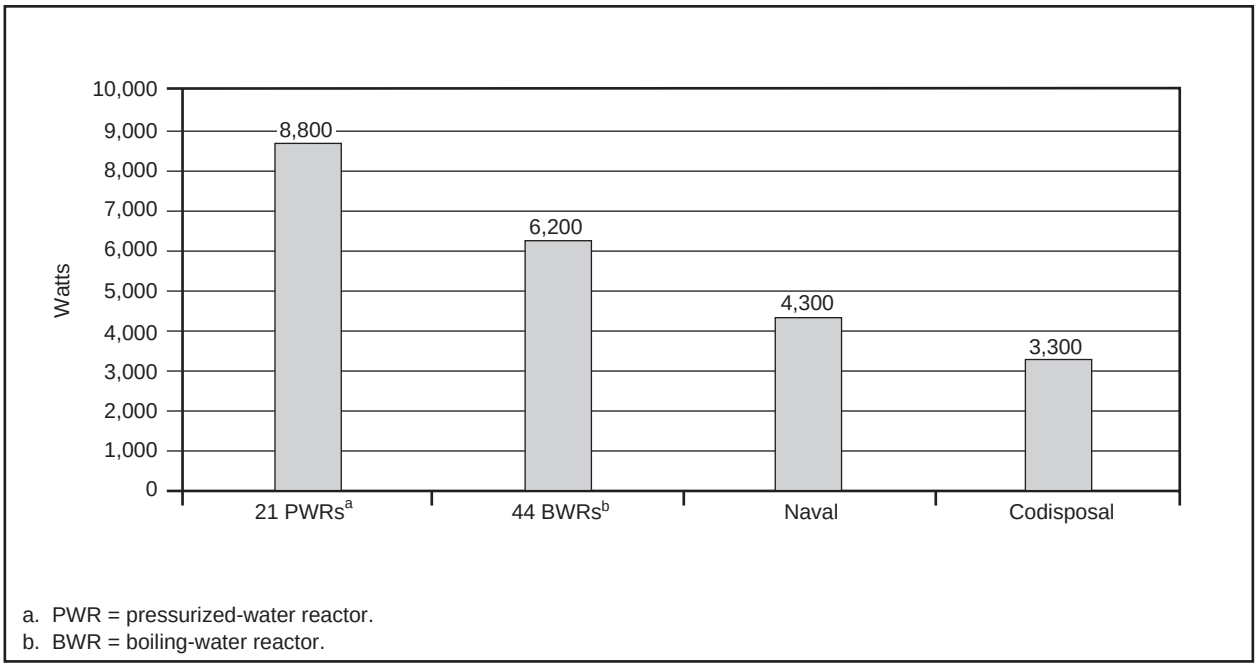
For DOE spent nuclear fuel and high-level radioactive waste, this appendix contains tables that describe the composition of the total inventory of the spent nuclear fuel (by representative category) or high-level radioactive waste (by site).

The chemical composition data were used primarily in the repository performance assessment (see Chapter 5 and Appendix I) to evaluate the relative amounts of materials that would need further study.



a. Pu = surplus weapons-usable plutonium; included in Proposed Action as spent nuclear fuel and high-level radioactive waste.
b. HLW = high-level radioactive waste.
c. DSNF = DOE spent nuclear fuel.
d. CSNF = commercial spent nuclear fuel
e. Cs = Cesium
f. Tc = Technetium
g. Np = Neptunium

Figure A-4. Proposed Action radionuclide distribution by material type.



a. PWR = pressurized-water reactor.
b. BWR = boiling-water reactor.

Figure A-5. Thermal generation (watts per waste package).

As a result of an initial screening, the repository performance assessment evaluated the long-term impacts of molybdenum, uranium, and chromium in the repository.

A.1.1.4.4 *Thermal Output*

Thermal generation data associated with each material type are provided in this appendix. These data were used to develop the thermal loads associated with the repository design. Chapter 2 describes the thermal load scenarios. The thermal data demonstrate that the EIS analysis can make simplifying assumptions that the thermal output of the commercial spent nuclear fuel waste packages, particularly the pressurized-water reactor assemblies, would bound the thermal output of all other waste packages (see Figure A-5).

The data presented in the thermal output sections of this appendix for each waste type are presented as watts per assembly or MTHM for commercial spent nuclear fuel, and watts per canister for DOE spent nuclear fuel or high-level radioactive waste. Figure A-5 normalizes these data into a common, watts-per-waste-package comparison. The following waste packages are compared: one containing 21 typical pressurized-water reactor assemblies, one containing 44 typical boiling-water reactor assemblies, a co-disposal waste package containing five high-level radioactive waste canisters and one DOE spent nuclear fuel canister, and a waste package containing one dual-purpose canister of naval spent nuclear fuel (also a DOE spent fuel). Another potential waste package containing four multi-canister overpacks of DOE uranium metal fuels is not included in Figure A-5 because its estimated maximum thermal generation is only 72 watts per waste package.

Figure A-5 uses conservative assumptions to illustrate the bounding nature of the thermal data for commercial spent nuclear fuel. The commercial spent nuclear fuel data represent typical assemblies that are assumed to have cooled for nearly 30 years. The naval spent nuclear fuel data are a best estimate of the thermal generation of 5-year old spent nuclear fuel. The thermal data selected for the high-level radioactive waste are conservatively represented by the canisters from the Savannah River Site and are combined with the highest values of thermal output from all projected DOE spent nuclear fuel categories.

A.1.1.4.5 *Canister Data*

Typically, DOE spent nuclear fuel and high-level radioactive waste would be sent to the repository in disposable canisters. The design specifications for DOE spent nuclear fuel canisters are in DOE (1998c, all). These canisters are generally of two diameters—46 and 61 centimeters (18 and 24 inches). They also would be designed for two different lengths, nominally 3 and 4.6 meters (10 and 15 feet), to enable co-disposal with high-level radioactive waste canisters. Certain DOE spent nuclear fuel categories require specific disposal canister designs. Naval fuels would be sent to the repository in Navy dual-purpose canisters, which are described in Dirkmaat (1997a, Attachment, pages 86 to 88) and USN (1996, pages 3-1 to 3-11). N-Reactor fuels from the Hanford Site would be sent to the repository in multicanister overpacks 64 centimeters (25.3 inches) in diameter, which are described in Parsons (1999, all).

High-level radioactive waste would be sent to the repository in stainless-steel canisters, 61 centimeters (25 inches) in diameter and either 3 or 4.6 meters (10 or 15 feet) in length, depending on the DOE site. The canister design specifications are contained in Marra, Harbour, and Plodinec (1995, all) and WVNS (1996, WQR-2.2, all) for the operating vitrification processes at Savannah River Site and West Valley Demonstration Project, respectively. The other sites would use canister designs similar to those currently in use (Picha 1997, all).

These data were for analysis of the No-Action Alternative (see Chapter 7 and Appendix K) to determine the time required to breach the canisters after they are exposed to weather elements.

A.2 Materials

This section describes the characteristics of the materials DOE has considered for disposal in the proposed Yucca Mountain Repository. All candidate materials would have to meet approved acceptance criteria.

A.2.1 COMMERCIAL SPENT NUCLEAR FUEL

A.2.1.1 Background

Spent nuclear fuel is fuel that has been withdrawn from a nuclear reactor following irradiation. Spent nuclear fuel from light-water reactors (pressurized-water and boiling-water reactors) would be the primary source of radioactivity and thermal load in the proposed monitored geologic repository. Spent nuclear fuels from civilian research reactors (General Atomics, Aerotest, etc.) account for less than 0.001 percent of the projected total in the Proposed Action (DOE 1995a, all). The fuels addressed in this section are those discharged from commercial light-water reactors.

Section A.2.2 discusses the spent nuclear fuel from the Fort St. Vrain reactor in Colorado as part of DOE spent nuclear fuels, as are the fuels from Shippingport, Three Mile Island-2, and other fuels from commercial facilities that DOE is managing at its facilities.

A.2.1.2 Sources

The sources of commercial spent nuclear fuel are the commercial nuclear powerplants throughout the country. Table A-3 lists the individual reactors, reactor type, state, and actual or projected years of operation. The operation period is subject to change if a utility pursues extension of the operating license or shuts down early.

A.2.1.3 Present Status

Nuclear power reactors store spent nuclear fuel in spent fuel pools under U.S. Nuclear Regulatory Commission licenses, but they can use a combination of storage options: (1) in-pool storage and (2) above-grade dry storage in an independent spent fuel storage installation. When a reactor is refueled, spent fuel is transferred to the spent fuel pool, where it typically remains until the available pool capacity is reached. When in-pool storage capacity has been fully used, utilities have turned to dry cask storage in an independent spent fuel storage installation to expand their onsite spent fuel storage capacities. In 1990, the Nuclear Regulatory Commission amended its regulations to authorize licensees to store spent nuclear fuel at reactor sites in approved storage casks (Raddatz and Waters 1996, all).

Commercial nuclear utilities currently use three Nuclear Regulatory Commission-approved general dry storage system design types—metal storage casks and metal canisters housed in concrete casks and concrete vaults—for use in licensed independent spent fuel storage installations. Raddatz and Waters (1996, all) contains detailed information on models currently approved by the Commission. Table A-4 lists existing and planned independent spent fuel storage installations in the United States.

A.2.1.4 Final Spent Nuclear Fuel Form

The final form of commercial spent nuclear fuel to be disposed of in the proposed repository would be the current reactor fuel assemblies. The repository would receive bare spent nuclear fuel assemblies, spent nuclear fuel packaged in canisters not intended for disposal, and spent nuclear fuel packaged in canisters intended for disposal.

Table A-3. Commercial nuclear power reactors in the United States and their projected years of operation.[a]

Unit name	Reactor type[b]	State	Operations period[c]	Unit name	Reactor type[b]	State	Operations period[c]
Arkansas Nuclear One 1	PWR	AR	1974-2014	Millstone 3	PWR	CT	1986-2025
Arkansas Nuclear One 2	PWR	AR	1978-2018	Monticello	BWR	MN	1971-2010
Beaver Valley 1	PWR	PA	1976-2016	Nine Mile Point 1	BWR	NY	1969-2009
Beaver Valley 2	PWR	PA	1978-2018	Nine Mile Point 2	BWR	NY	1987-2026
Big Rock Point	BWR	MI	1963-1997	North Anna 1	PWR	VA	1978-2018
Braidwood 1	PWR	IL	1987-2026	North Anna 2	PWR	VA	1980-2020
Braidwood 2	PWR	IL	1988-2027	Oconee 1	PWR	SC	1973-2013
Browns Ferry 1	BWR	AL	1973-2013	Oconee 2	PWR	SC	1973-2013
Browns Ferry 2	BWR	AL	1974-2014	Oconee 3	PWR	SC	1974-2014
Browns Ferry 3	BWR	AL	1976-2016	Oyster Creek	BWR	NJ	1969-2009
Brunswick 1	BWR	NC	1976-2016	Palisades	PWR	MI	1972-2007
Brunswick 2	BWR	NC	1974-2014	Palo Verde 1	PWR	AZ	1985-2024
Byron 1	PWR	IL	1985-2024	Palo Verde 2	PWR	AZ	1986-2025
Byron 2	PWR	IL	1987-2026	Palo Verde 3	PWR	AZ	1987-2027
Callaway	PWR	MO	1984-2024	Peach Bottom 2	BWR	PA	1973-2013
Calvert Cliffs 1	PWR	MD	1974-2014	Peach Bottom 3	BWR	PA	1974-2014
Calvert Cliffs 2	PWR	MD	1976-2016	Perry 1	BWR	OH	1986-2026
Catawba 1	PWR	SC	1985-2024	Pilgrim 1	BWR	MA	1972-2012
Catawba 2	PWR	SC	1986-2026	Point Beach 1	PWR	WI	1970-2010
Clinton	BWR	IL	1987-2026	Point Beach 2	PWR	WI	1973-2013
Comanche Peak 1	PWR	TX	1990-2030	Prairie Island 1	PWR	MN	1974-2013
Comanche Peak 2	PWR	TX	1993-2033	Prairie Island 2	PWR	MN	1974-2014
Cooper Station	BWR	NE	1974-2014	Quad Cities 1	BWR	IL	1972-2012
Crystal River 3	PWR	FL	1977-2016	Quad Cities 2	BWR	IL	1972-2012
D. C. Cook 1	PWR	MI	1974-2014	Rancho Seco	PWR	CA	1974-1989
D. C. Cook 2	PWR	MI	1977-2017	River Bend 1	BWR	LA	1985-2025
Davis-Besse	PWR	OH	1977-2017	Salem 1	PWR	NJ	1976-2016
Diablo Canyon 1	PWR	CA	1984-2021	Salem 2	PWR	NJ	1981-2020
Diablo Canyon 2	PWR	CA	1985-2025	San Onofre 1	PWR	CA	1967-1992
Dresden 1	BWR	IL	1959-1978	San Onofre 2	PWR	CA	1982-2013
Dresden 2	BWR	IL	1969-2006	San Onofre 3	PWR	CA	1983-2013
Dresden 3	BWR	IL	1971-2011	Seabrook 1	PWR	NH	1990-2026
Duane Arnold 1	BWR	IA	1974-2014	Sequoyah 1	PWR	TN	1980-2020
Edwin I. Hatch 1	BWR	GA	1974-2014	Sequoyah 2	PWR	TN	1981-2021
Edwin I. Hatch 2	BWR	GA	1978-2018	Shearon Harris	PWR	NC	1987-2026
Fermi 2	BWR	MI	1985-2025	Shoreham	BWR	NY	1989[d]
Fort Calhoun 1	PWR	NE	1973-2013	South Texas Project 1	PWR	TX	1988-2016
Ginna	PWR	NY	1969-2009	South Texas Project 2	PWR	TX	1989-2023
Grand Gulf 1	BWR	MS	1984-2022	St. Lucie 1	PWR	FL	1976-2016
Haddam Neck	PWR	CT	1968-1996	St. Lucie 2	PWR	FL	1983-2023
Hope Creek	BWR	NJ	1986-2026	Summer 1	PWR	SC	1982-2022
Humboldt Bay	BWR	CA	1962-1976	Surry 1	PWR	VA	1972-2012
H.B. Robinson 2	PWR	SC	1970-2010	Surry 2	PWR	VA	1973-2013
Indian Point 1	PWR	NY	1962-1974	Susquehanna 1	BWR	PA	1982-2022
Indian Point 2	PWR	NY	1973-2013	Susquehanna 2	BWR	PA	1984-2024
Indian Point 3	PWR	NY	1976-2015	Three Mile Island 1	PWR	PA	1974-2014
James A. FitzPatrick/ Nine Mile Point	BWR	NY	1974-2014	Trojan	PWR	OR	1975-1992
				Turkey Point 3	PWR	FL	1972-2012
Joseph M. Farley 1	PWR	AL	1977-2017	Turkey Point 4	PWR	FL	1973-2013
Joseph M. Farley 2	PWR	AL	1981-2021	Vermont Yankee	BWR	VT	1973-2012
Kewaunee	PWR	WI	1973-2013	Vogtle 1	PWR	GA	1987-2027
LaCrosse	BWR	WI	1967-1987	Vogtle 2	PWR	GA	1989-2029
LaSalle 1	BWR	IL	1970-2022	Washington Public Power Supply System 2	BWR	WA	1984-2023
LaSalle 2	BWR	IL	1970-2023				
Limerick 1	BWR	PA	1985-2024	Waterford 3	PWR	LA	1985-2024
Limerick 2	BWR	PA	1989-2029	Watts Bar 1	PWR	TN	1996-2035
Maine Yankee	PWR	ME	1972-1996	Wolf Creek	PWR	KS	1985-2025
McGuire 1	PWR	NC	1981-2021	Yankee-Rowe	PWR	MA	1963-1991
McGuire 2	PWR	NC	1983-2023	Zion 1	PWR	IL	1973-1997
Millstone 1	BWR	CT	1970-2010	Zion 2	PWR	IL	1974-1996
Millstone 2	PWR	CT	1975-2015				

a. Source: DOE (1997a, Appendix C).
b. PWR = pressurized-water reactor; BWR = boiling-water reactor.
c. As defined by current shutdown or full operation through license period (as of 1997).
d. Shoreham is no longer a licensed plant and has transferred all fuel to Limerick.

Table A-4. Sites with existing or planned independent spent fuel storage installations.[a]

Reactor	Status	Reactor	Status
Prairie Island	Existing	Rancho Seco	Planned
Point Beach	Existing	Trojan	Planned
Palisades	Existing	Washington Public Power Supply System	Planned
Surry	Existing	Big Rock Point	Planned
Calvert Cliffs	Existing	Oyster Creek	Planned
Arkansas Nuclear	Existing	Duane Arnold	Planned
H. B. Robinson	Existing	McGuire	Planned
Oconee	Existing	Yankee Rowe	Planned
Davis-Besse	Existing	Maine Yankee	Planned
North Anna	Planned	Peach Bottom	Planned
James A. FitzPatrick/Nine Mile Point	Planned	Palo Verde	Planned
Dresden	Planned	Humboldt Bay	Planned
Susquehanna	Planned		

a. Sources: Raddatz and Waters (1996, all); Cole (1998a, all).

A.2.1.5 Spent Nuclear Fuel Characteristics

There are 22 classes of nuclear fuel assemblies, with 127 individual fuel types in those classes. Seventeen of the classes are for pressurized-water reactor fuels and 5 are for boiling-water reactors (DOE 1992, Appendix 2A). For this EIS, the typical assemblies chosen for analysis represent an assembly type being used in the more recently built reactors. This results in physical characteristics that might be slightly higher than average (size, uranium per assembly, etc.), but that, however, provide a realistic estimate for EIS analyses. Specifically chosen to represent the typical fuel types were the Westinghouse 17 × 17 LOPAR fuel assembly for the pressurized-water reactor and the General Electric BWR/4-6, 8 × 8 fuel assembly for the boiling-water reactor. Table A-5 lists the fissile content and performance parameters selected to define the radiological characteristics of these typical fuel assemblies.

Table A-5. Typical spent nuclear fuel parameters.[a]

Fuel type[b]	Burnup (MWd/MTHM)[c]	Initial enrichment (percent of U-235 by weight)	Age (years)
Typical PWR	39,560	3.69	25.9
Typical BWR	32,240	3.00	27.2

a. Source: TRW (1998, page 3-15).
b. PWR = pressurized-water reactor; BWR = boiling-water reactor.
c. MWd/MTHM = megawatt-days per metric ton of heavy metal; to convert metric tons to tons, multiply by 1.1023.

A.2.1.5.1 *Mass and Volume*

As discussed in Section A.1, the Proposed Action includes 63,000 MTHM of commercial spent nuclear fuel. For the No-Action Alternative (continued storage) analysis, Table A-6 lists the distribution of this expected inventory by reactor site. The historic and projected spent nuclear fuel discharge and storage information in Table A-6 is consistent with the annual projections provided by the Energy Information Administration (DOE 1997a, page 32). The "1995 Actual" data presented in Table A-6 represents the amount of spent nuclear fuel stored at a particular site regardless of the reactor from which it was discharged. For analysis purposes, the table lists spent nuclear fuel currently stored at the General Electric Morris, Illinois, facility to be at Dresden, because these facilities are located near each other.

For analyses associated with the Proposed Action, the projected spent nuclear fuel from pressurized-water reactors comprises 65 percent of the 63,000 metric tons of heavy metal (TRW 1997, page A-2). The

Table A-6. Proposed Action spent nuclear fuel inventory (MTHM).[a]

Site	Fuel type[b]	1995 actual	1996-2011[c]	Total[d]	Equivalent assemblies	Site	Fuel type[b]	1995 actual	1996-2011[c]	Total[d]	Equivalent assemblies
Arkansas Nuclear One	PWR	643	466	1,109	2,526	Monticello	BWR	147	280	426	2,324
Beaver Valley	PWR	437	581	1,018	2,206	North Anna	PWR	570	613	1,184	2,571
Big Rock Point	BWR	44	14	58	439	Oconee	PWR	1,098	767	1,865	4,028
Braidwood	PWR	318	711	1,029	2,424	Oyster Creek	BWR	374	325	699	3,824
Browns Ferry	BWR	840	1,092	1,932	10,402	Palisades	PWR	338	247	585	1,473
Brunswick	Both	448	448	896	4,410	Palo Verde	PWR	556	1,118	1,674	4,082
Byron	PWR	404	664	1,068	2,515	Peach Bottom	BWR	908	645	1,554	8,413
Callaway	PWR	280	422	702	1,609	Perry	BWR	178	274	452	2,470
Calvert Cliffs	PWR	641	501	1,142	2,982	Pilgrim	BWR	326	201	527	2,853
Catawba	PWR	465	683	1,148	2,677	Point Beach	PWR	529	347	876	2,270
Clinton	BWR	174	303	477	2,588	Prairie Island	PWR	518	348	866	2,315
Comanche Peak	PWR	176	821	998	2,202	Quad Cities	BWR	813	464	1,277	6,953
Cooper	BWR	175	277	452	2,435	Rancho Seco	PWR	228	--[e]	228	493
Crystal River	PWR	280	232	512	1,102	River Bend	BWR	176	356	531	2,889
D. C. Cook	PWR	777	656	1,433	3,253	Salem/Hope Creek	Both	793	866	1,659	7,154
Davis-Besse	PWR	243	262	505	1,076	San Onofre	PWR	722	701	1,423	3,582
Diablo Canyon	PWR	463	664	1,126	2,512	Seabrook	PWR	133	292	425	918
Dresden	BWR	1,557	590	2,146	11,602	Sequoyah	PWR	452	570	1,023	2,218
Duane Arnold	BWR	258	208	467	2,545	Shearon Harris	Both	498	252	750	2,499
Edwin I. Hatch	BWR	755	692	1,446	7,862	South Texas Project	PWR	290	722	1,012	1,871
Fermi	BWR	155	368	523	2,898	St. Lucie	PWR	601	419	1,020	2,701
Fort Calhoun	PWR	222	157	379	1,054	Summer	PWR	225	301	526	1,177
Ginna	PWR	282	180	463	1,234	Surry	PWR	660	534	1,194	2,604
Grand Gulf	BWR	349	506	856	4,771	Susquehanna	BWR	628	648	1,276	7,172
H. B. Robinson	PWR	145	239	384	903	Three Mile Island	PWR	311	236	548	1,180
Haddam Neck	PWR	355	65	420	1,017	Trojan	PWR	359	--	359	780
Humboldt Bay	BWR	29	--	29	390	Turkey Point	PWR	616	458	1,074	2,355
Indian Point	PWR	678	486	1,164	2,649	Vermont Yankee	BWR	387	222	609	3,299
James A. FitzPatrick/ Nine Mile Point	BWR	882	930	1,812	9,830	Vogtle	PWR	335	745	1,080	2,364
Joseph M. Farley	PWR	644	530	1,174	2,555	Washington Public Power Supply System 2	BWR	243	338	581	3,223
Kewaunee	PWR	282	169	451	1,172						
La Crosse	BWR	38	--	38	333	Waterford	PWR	253	247	500	1,217
La Salle	BWR	465	487	952	5,189	Watts Bar	PWR	--	251	251	544
Limerick	BWR	432	711	1,143	6,203	Wolf Creek	PWR	226	404	630	1,360
Maine Yankee	PWR	454	82	536	1,421	Yankee-Rowe	PWR	127	--	127	533
McGuire	PWR	714	725	1,439	3,257	Zion	PWR	841	211	1,052	2,302
Millstone	Both	959	749	1,709	6,447	**Totals**		**31,926**	**31,074**	**63,000**	**218,700**

a. Source: Heath (1998, Appendixes B and C).
b. PWR = pressurized-water reactor; BWR = boiling-water reactor.
c. Projected.
d. To convert metric tons to tons, multiply by 1.1023.
e. -- = no spent nuclear fuel production.

balance consists of spent nuclear fuel from boiling-water reactors. Using the nominal volume for the spent nuclear fuel assemblies described in Section A.2.1.5.5, the estimated volume of spent nuclear fuel in the Proposed Action, exclusive of packaging, is 29,000 cubic meters.

Section A.1 also discusses the additional inventory modules evaluated in this EIS. Inventory Modules 1 and 2 both include the maximum expected discharge inventory of commercial spent nuclear fuel. Table A-7 lists historic and projected amounts of spent nuclear fuel discharged from commercial reactors through 2046. The estimated unpackaged volume of spent nuclear fuel for these modules is approximately 47,000 cubic meters. For conservatism, these data were derived from the Energy Information Administration "high case" assumptions. The high case assumes that all currently operating nuclear units would renew their operating licenses for an additional 10 years (DOE 1997a, page 32).

Table A-7. Inventory Modules 1 and 2 spent nuclear fuel inventory (MTHM).[a]

Site	Fuel type[b]	1995 actual	1996-2046[c]	Total[d]	Equivalent assemblies	Site	Fuel type[b]	1995 actual	1996-2046[c]	Total[d]	Equivalent assemblies
Arkansas Nuclear One	PWR	643	1,007	1,650	3,757	Monticello	BWR	147	390	537	2,924
Beaver Valley	PWR	437	1,395	1,832	3,970	North Anna	PWR	570	1,384	1,955	4,246
Big Rock Point	BWR	44	14	58	439	Oconee	PWR	1,098	1,576	2,674	5,774
Braidwood	PWR	318	1,969	2,287	5,385	Oyster Creek	BWR	374	470	844	4,619
Browns Ferry	BWR	840	2,508	3,348	18,024	Palisades	PWR	338	395	733	1,845
Brunswick	Both	448	992	1,440	7,355	Palo Verde	PWR	556	3,017	3,573	8,712
Byron	PWR	404	1,777	2,181	5,139	Peach Bottom	BWR	908	1,404	2,312	12,523
Callaway	PWR	280	1,008	1,288	2,953	Perry	BWR	178	732	910	4,974
Calvert Cliffs	PWR	641	1,069	1,710	4,466	Pilgrim	BWR	326	444	770	4,170
Catawba	PWR	465	1,752	2,217	5,168	Point Beach	PWR	529	614	1,143	2,961
Clinton	BWR	174	910	1,084	5,876	Prairie Island	PWR	518	692	1,210	3,234
Comanche Peak	PWR	176	2,459	2,635	5,816	Quad Cities	BWR	813	1,020	1,834	9,982
Cook	PWR	777	1,379	2,155	4,892	Rancho Seco	PWR	228	--[e]	228	493
Cooper	BWR	175	587	762	4,106	River Bend	BWR	176	956	1,132	6,153
Crystal River	PWR	280	525	805	1,734	Salem/Hope Creek	Both	793	2,452	3,245	11,584
Davis-Besse	PWR	243	582	825	1,757	San Onofre	PWR	722	1,321	2,043	5,144
Diablo Canyon	PWR	463	1,725	2,187	4,878	Seabrook	PWR	133	831	964	2,083
Dresden	BWR	1,557	984	2,541	13,740	Sequoyah	PWR	452	1,393	1,845	4,001
Duane Arnold	BWR	258	434	692	3,776	Shearon Harris	Both	498	707	1,205	3,535
Fermi	BWR	155	1,005	1,160	6,429	South Texas Project	PWR	290	2,029	2,319	4,286
Fort Calhoun	PWR	222	312	534	1,485	St. Lucie	PWR	601	1,010	1,611	4,265
Ginna	PWR	282	283	565	1,507	Summer	PWR	225	732	958	2,141
Grand Gulf	BWR	349	1,261	1,610	8,976	Surry	PWR	660	1,029	1,689	3,682
H. B. Robinson	PWR	145	364	509	1,197	Susquehanna	BWR	628	1,745	2,373	13,338
Haddam Neck	PWR	355	65	420	1,017	Three Mile Island	PWR	311	513	825	1,777
Hatch	BWR	755	1,517	2,272	12,347	Trojan	PWR	359	--	359	780
Humboldt Bay	BWR	29	--	29	390	Turkey Point	PWR	616	905	1,520	3,334
Indian Point	PWR	678	1,005	1,683	3,787	Vermont Yankee	BWR	387	434	822	4,451
James A. FitzPatrick/ Nine Mile Point	BWR	882	2,018	2,900	15,732	Vogtle	PWR	335	2,122	2,458	5,378
Joseph M. Farley	PWR	644	1,225	1,869	4,070	Washington Public Power Supply System 2	BWR	243	924	1,167	6,476
Kewaunee	PWR	282	330	612	1,591						
La Crosse	BWR	38	--	38	333	Waterford	PWR	253	685	938	2,282
La Salle	BWR	465	1,398	1,863	10,152	Watts Bar	PWR	--	893	893	1,937
Limerick	BWR	432	1,958	2,390	12,967	Wolf Creek	PWR	226	1,052	1,278	2,759
Maine Yankee	PWR	454	82	536	1,421	Yankee-Rowe	PWR	127	--	127	533
McGuire	PWR	714	1,813	2,527	5,720	Zion	PWR	841	211	1,052	2,302
Millstone	Both	959	1,695	2,655	8,930	**Totals**		**31,926**	**73,488**	**105,414**	**359,963**

a. Source: Heath (1998, Appendixes B and C).
b. PWR = pressurized-water reactor; BWR = boiling-water reactor.
c. Projected.
d. To convert metric tons to tons, multiply by 1.1023.
e. -- = no spent nuclear fuel production.

A.2.1.5.2 *Amount and Nature of Radioactivity*

DOE derived radionuclide inventories for the typical pressurized-water reactor and boiling-water reactor fuel assemblies from the Light-Water Reactor Radiological Database (DOE 1992, page 1.1-1). The inventories are presented at the average decay years for each of the typical assemblies. Tables A-8 and A-9 list the inventories of the nuclides of interest for the typical assemblies for both reactor types.

Table A-10 combines the typical inventories (curies per MTHM) with the projected totals (63,000 MTHM and 105,000 MTHM) to provide a total projected radionuclide inventory for the Proposed Action and additional modules.

A.2.1.5.3 *Chemical Composition*

Commercial spent nuclear fuel consists of the uranium oxide fuel itself (including actinides, fission products, etc.), the cladding, and the assembly hardware.

Table A-8. Radionuclide activity for typical pressurized-water reactor fuel assemblies.[a,b]

Isotope	Curies per assembly	Isotope	Curies per assembly	Isotope	Curies per assembly
Hydrogen-3	9.8×10^{1}	Cesium-134	1.6×10^{1}	Neptunium-237	2.3×10^{-1}
Carbon-14	6.4×10^{-1}	Cesium-135	2.5×10^{-1}	Plutonium-238	1.7×10^{3}
Chlorine-36	5.4×10^{-3}	Cesium-137	3.1×10^{4}	Plutonium-239	1.8×10^{2}
Cobalt-60	1.5×10^{2}	Samarium-151	1.9×10^{2}	Plutonium-240	2.7×10^{2}
Nickel-59	1.3	Lead-210	2.2×10^{-7}	Plutonium-241	2.0×10^{4}
Nickel-63	1.8×10^{2}	Radium-226	9.3×10^{-7}	Plutonium-242	9.9×10^{-1}
Selenium-79	2.3×10^{-1}	Radium-228	1.3×10^{-10}	Americium-241	1.7×10^{3}
Krypton-85	9.3×10^{2}	Actinium-227	7.8×10^{-6}	Americium-242/242m	1.1×10^{1}
Strontium-90	2.1×10^{4}	Thorium-229	1.7×10^{-7}	Americium-243	1.3×10^{1}
Zirconium-93	1.2	Thorium-230	1.5×10^{-4}	Curium-242	8.7
Niobium-93m	8.2×10^{-1}	Thorium-232	1.9×10^{-10}	Curium-243	8.3
Niobium-94	5.8×10^{-1}	Protactinium-231	1.6×10^{-5}	Curium-244	7.0×10^{2}
Technetium-99	7.1	Uranium-232	1.9×10^{-2}	Curium-245	1.8×10^{-1}
Rhodium-102	1.2×10^{-3}	Uranium-233	3.3×10^{-5}	Curium-246	3.8×10^{-2}
Ruthenium-106	4.8×10^{-3}	Uranium-234	6.6×10^{-1}	Curium-247	1.3×10^{-7}
Palladium-107	6.3×10^{-2}	Uranium-235	8.4×10^{-3}	Curium-248	3.9×10^{-7}
Tin-126	4.4×10^{-1}	Uranium-236	1.4×10^{-1}	Californium-252	3.1×10^{-8}
Iodine-129	1.8×10^{-2}	Uranium-238	1.5×10^{-1}		

a. Source: DOE (1992, page 1.1-1).
b. Burnup = 39,560 MWd/MTHM, enrichment = 3.69 percent, decay time = 25.9 years.

Table A-9. Radionuclide activity for typical boiling-water reactor fuel assemblies.[a,b]

Isotope	Curies per assembly	Isotope	Curies per assembly	Isotope	Curies per assembly
Hydrogen-3	3.4×10^{1}	Cesium-134	3.4	Neptunium-237	7.3×10^{-2}
Carbon-14	3.0×10^{-1}	Cesium-135	1.0×10^{-1}	Plutonium-238	5.5×10^{2}
Chlorine-36	2.2×10^{-3}	Cesium-137	1.1×10^{4}	Plutonium-239	6.3×10^{1}
Cobalt-60	3.7×10^{1}	Samarium-151	6.6×10^{1}	Plutonium-240	9.5×10^{1}
Nickel-59	3.5×10^{-1}	Lead-210	9.4×10^{-8}	Plutonium-241	7.5×10^{3}
Nickel-63	4.6×10^{1}	Radium-226	3.7×10^{-7}	Plutonium-242	4.0×10^{-1}
Selenium-79	7.9×10^{-2}	Radium-228	4.7×10^{-11}	Americium-241	6.8×10^{2}
Krypton-85	2.9×10^{2}	Actinium-227	3.1×10^{-6}	Americium-242/242m	4.6
Strontium-90	7.1×10^{3}	Thorium-229	6.1×10^{-8}	Americium-243	4.9
Zirconium-93	4.8×10^{-1}	Thorium-230	5.8×10^{-5}	Curium-242	3.8
Niobium-93m	3.5×10^{-1}	Thorium-232	6.9×10^{-11}	Curium-243	3.1
Niobium-94	1.9×10^{-2}	Protactinium-231	6.0×10^{-6}	Curium-244	2.5×10^{2}
Technetium-99	2.5	Uranium-232	5.5×10^{-3}	Curium-245	6.3×10^{-2}
Rhodium-102	2.8×10^{-4}	Uranium-233	1.1×10^{-5}	Curium-246	1.3×10^{-2}
Ruthenium-106	6.7×10^{-4}	Uranium-234	2.4×10^{-1}	Curium-247	4.3×10^{-8}
Palladium-107	2.4×10^{-2}	Uranium-235	3.0×10^{-3}	Curium-248	1.2×10^{-7}
Tin-126	1.5×10^{-1}	Uranium-236	4.8×10^{-2}	Californium-252	6.0×10^{-9}
Iodine-129	6.3×10^{-3}	Uranium-238	6.2×10^{-2}		

a. Source: DOE (1992, page 1.1-1).
b. Burnup = 32,240 MWd/MTHM, enrichment = 3.00 percent, decay time = 27.2 years.

Typical pressurized-water and boiling-water reactor fuels consist of uranium dioxide with a zirconium alloy cladding. Some assemblies, however, are clad in stainless-steel 304. Specifically, 2,187 assemblies, or 727 MTHM (1.15 percent of the MTHM included in the Proposed Action) are stainless-steel clad (Cole 1998b, all). These assemblies have been discharged from Haddam Neck, Yankee-Rowe, Indian Point, San Onofre, and LaCrosse. Table A-11 lists the number of assemblies discharged, MTHM, and storage sites for each plant.

Tables A-12 and A-13 list the postirradiation elemental distributions for typical fuels. The data in these tables include the fuel, cladding material, and assembly hardware.

Table A-10. Total projected radionuclide inventories.[a]

	Pressurized-water reactor			Boiling-water reactor				
		Total curies			Total curies		Grand totals (curies)	
Isotope	Curies per MTHM[b]	Proposed Action	Additional modules	Curies per MTHM	Proposed Action	Additional modules	Proposed Action	Additional modules
Hydrogen-3	2.1×10^{2}	8.6×10^{6}	1.4×10^{7}	1.7×10^{2}	3.8×10^{6}	6.4×10^{6}	1.2×10^{7}	2.1×10^{7}
Carbon-14	1.4	5.7×10^{4}	9.5×10^{4}	1.5	3.4×10^{4}	5.7×10^{4}	9.1×10^{4}	1.5×10^{5}
Chlorine-36	1.2×10^{-2}	4.7×10^{2}	7.9×10^{2}	1.1×10^{-2}	2.5×10^{2}	4.1×10^{2}	7.2×10^{2}	1.2×10^{3}
Cobalt-60	3.2×10^{2}	1.3×10^{7}	2.2×10^{7}	1.9×10^{2}	4.2×10^{6}	7.0×10^{6}	1.7×10^{7}	2.9×10^{7}
Nickel-59	2.8	1.1×10^{5}	1.9×10^{5}	1.8	4.0×10^{4}	6.6×10^{4}	1.5×10^{5}	2.6×10^{5}
Nickel-63	3.8×10^{2}	1.6×10^{7}	2.6×10^{7}	2.3×10^{2}	5.1×10^{6}	8.6×10^{6}	2.1×10^{7}	3.5×10^{7}
Selenium-79	4.9×10^{-1}	2.0×10^{4}	3.3×10^{4}	4.0×10^{-1}	8.9×10^{3}	1.5×10^{4}	2.9×10^{4}	4.8×10^{4}
Krypton-85	2.0×10^{3}	8.2×10^{7}	1.4×10^{8}	1.5×10^{3}	3.3×10^{7}	5.5×10^{7}	1.1×10^{8}	1.9×10^{8}
Strontium-90	4.6×10^{4}	1.9×10^{9}	3.1×10^{9}	3.6×10^{4}	8.0×10^{8}	1.3×10^{9}	2.7×10^{9}	4.5×10^{9}
Zirconium-93	2.5	1.0×10^{5}	1.7×10^{5}	2.4	5.4×10^{4}	9.0×10^{4}	1.6×10^{5}	2.6×10^{5}
Niobium-93m	1.8	7.3×10^{4}	1.2×10^{5}	1.8	3.9×10^{4}	6.6×10^{4}	1.1×10^{5}	1.9×10^{5}
Niobium-94	1.3	5.1×10^{4}	8.6×10^{4}	9.8×10^{-2}	2.2×10^{3}	3.6×10^{3}	5.3×10^{4}	8.9×10^{4}
Technetium-99	1.5×10^{1}	6.3×10^{5}	1.1×10^{6}	1.3×10^{1}	2.9×10^{5}	4.8×10^{5}	9.2×10^{5}	1.5×10^{6}
Rhodium-102	2.6×10^{-3}	1.1×10^{2}	1.8×10^{2}	1.4×10^{-3}	3.2×10^{1}	5.3×10^{1}	1.4×10^{2}	2.3×10^{2}
Ruthenium-106	1.0×10^{-2}	4.2×10^{2}	7.0×10^{2}	3.4×10^{-3}	7.5×10^{1}	1.3×10^{2}	5.0×10^{2}	8.3×10^{2}
Palladium-107	1.4×10^{-1}	5.6×10^{3}	9.4×10^{3}	1.2×10^{-1}	2.7×10^{3}	4.5×10^{3}	8.3×10^{3}	1.4×10^{4}
Tin-126	9.4×10^{-1}	3.8×10^{4}	6.4×10^{4}	7.9×10^{-1}	1.7×10^{0}	2.9×10^{4}	5.6×10^{4}	9.3×10^{4}
Iodine-129	3.8×10^{-2}	1.5×10^{3}	2.6×10^{3}	3.2×10^{-2}	7.0×10^{2}	1.2×10^{3}	2.2×10^{3}	3.8×10^{3}
Cesium-134	3.5×10^{1}	1.4×10^{6}	2.4×10^{6}	1.7×10^{1}	3.8×10^{5}	6.4×10^{5}	1.8×10^{6}	3.0×10^{6}
Cesium-135	5.5×10^{-1}	2.3×10^{4}	3.8×10^{4}	5.1×10^{-1}	1.1×10^{4}	1.9×10^{4}	3.4×10^{4}	5.6×10^{4}
Cesium-137	6.7×10^{4}	2.8×10^{9}	4.6×10^{9}	5.4×10^{4}	1.2×10^{9}	2.0×10^{9}	4.0×10^{9}	6.6×10^{9}
Samarium-151	4.0×10^{2}	1.6×10^{7}	2.7×10^{7}	3.4×10^{2}	7.4×10^{0}	1.2×10^{7}	2.4×10^{7}	4.0×10^{7}
Lead-210	4.8×10^{-7}	2.0×10^{-2}	3.3×10^{-2}	4.8×10^{-7}	1.1×10^{-2}	1.8×10^{-2}	3.0×10^{-2}	5.1×10^{-2}
Radium-226	2.0×10^{-6}	8.2×10^{-2}	1.4×10^{-1}	1.9×10^{-6}	4.2×10^{-2}	7.0×10^{-2}	1.2×10^{-1}	2.1×10^{-1}
Radium-228	2.8×10^{-10}	1.1×10^{-5}	1.9×10^{-5}	2.4×10^{-10}	5.3×10^{-6}	8.9×10^{-6}	1.7×10^{-5}	2.8×10^{-5}
Actinium-227	1.7×10^{-5}	6.9×10^{-1}	1.2	1.6×10^{-5}	3.5×10^{-1}	5.8×10^{-1}	1.0	1.7
Thorium-229	3.8×10^{-7}	1.5×10^{-2}	2.6×10^{-2}	3.1×10^{-7}	6.9×10^{-3}	1.2×10^{-2}	2.2×10^{-2}	3.7×10^{-2}
Thorium-230	3.3×10^{-4}	1.4×10^{1}	2.3×10^{1}	3.0×10^{-4}	6.6×10	1.1×10^{1}	2.0×10^{1}	3.4×10^{1}
Thorium-232	4.1×10^{-10}	1.7×10^{-5}	2.8×10^{-5}	3.5×10^{-10}	7.8×10^{-6}	1.3×10^{-5}	2.5×10^{-5}	4.1×10^{-5}
Protactinium-231	3.4×10^{-5}	1.4	2.3	3.1×10^{-5}	6.8×10^{-1}	1.1	2.1	3.5
Uranium-232	4.0×10^{-2}	1.6×10^{3}	2.7×10^{3}	2.8×10^{-2}	6.2×10^{2}	1.0×10^{3}	2.3×10^{3}	3.8×10^{3}
Uranium-233	7.1×10^{-5}	2.9	4.9	5.4×10^{-5}	1.2	2.0	4.1	6.9
Uranium-234	1.4	5.8×10^{4}	9.7×10^{4}	1.2	2.7×10^{4}	4.5×10^{4}	8.5×10^{4}	1.4×10^{5}
Uranium-235	1.8×10^{-2}	7.4×10^{2}	1.2×10^{3}	1.5×10^{-2}	3.4×10^{2}	5.6×10^{2}	1.1×10^{3}	1.8×10^{3}
Uranium-236	3.0×10^{-1}	1.2×10^{4}	2.1×10^{4}	2.4×10^{-1}	5.4×10^{3}	9.0×10^{3}	1.8×10^{4}	3.0×10^{4}
Uranium-238	3.1×10^{-1}	1.3×10^{4}	2.2×10^{4}	3.2×10^{-1}	7.0×10^{3}	1.2×10^{4}	2.0×10^{4}	3.3×10^{4}
Neptunium-237	4.9×10^{-1}	2.0×10^{4}	3.4×10^{4}	3.7×10^{-1}	8.2×10^{3}	1.4×10^{4}	2.8×10^{4}	4.7×10^{4}
Plutonium-238	3.6×10^{3}	1.5×10^{8}	2.5×10^{8}	2.8×10^{3}	6.1×10^{7}	1.0×10^{8}	2.1×10^{8}	3.5×10^{8}
Plutonium-239	3.9×10^{2}	1.6×10^{7}	2.7×10^{7}	3.2×10^{2}	7.1×10^{6}	1.2×10^{7}	2.3×10^{7}	3.9×10^{7}
Plutonium-240	5.8×10^{2}	2.4×10^{7}	4.0×10^{7}	4.9×10^{2}	1.1×10^{7}	1.8×10^{7}	3.4×10^{7}	5.8×10^{7}
Plutonium-241	4.4×10^{4}	1.8×10^{9}	3.0×10^{9}	3.8×10^{4}	8.4×10^{8}	1.4×10^{9}	2.6×10^{9}	4.4×10^{9}
Plutonium-242	2.1	8.7×10^{4}	1.5×10^{5}	2.0	4.5×10^{4}	7.5×10^{4}	1.3×10^{5}	2.2×10^{5}
Americium-241	3.7×10^{3}	1.5×10^{8}	2.5×10^{8}	3.5×10^{3}	7.7×10^{7}	1.3×10^{8}	2.3×10^{8}	3.8×10^{8}
Americium-242/242m	2.3×10^{1}	9.3×10^{5}	1.6×10^{6}	2.3×10^{1}	5.2×10^{5}	8.7×10^{5}	1.4×10^{6}	2.4×10^{6}
Americium-243	2.7×10^{1}	1.1×10^{6}	1.9×10^{6}	2.5×10^{1}	5.5×10^{5}	9.2×10^{5}	1.7×10^{6}	2.8×10^{6}
Curium-242	1.9×10^{1}	7.7×10^{5}	1.3×10^{6}	1.9×10^{1}	4.3×10^{5}	7.1×10^{5}	1.2×10^{6}	2.0×10^{6}
Curium-243	1.8×10^{1}	7.3×10^{5}	1.2×10^{6}	1.6×10^{1}	3.5×10^{5}	5.8×10^{5}	1.1×10^{6}	1.8×10^{6}
Curium-244	1.5×10^{3}	6.2×10^{7}	1.0×10^{8}	1.3×10^{3}	2.8×10^{7}	4.7×10^{7}	9.0×10^{7}	1.5×10^{8}
Curium-245	3.9×10^{-1}	1.6×10^{4}	2.7×10^{4}	3.2×10^{-1}	7.1×10^{3}	1.2×10^{4}	2.3×10^{4}	3.8×10^{4}
Curium-246	8.2×10^{-2}	3.4×10^{3}	5.6×10^{3}	6.5×10^{-2}	1.4×10^{3}	2.4×10^{3}	4.8×10^{3}	8.0×10^{3}
Curium-247	2.9×10^{-7}	1.2×10^{-2}	2.0×10^{-2}	2.2×10^{-7}	4.8×10^{-3}	8.1×10^{-3}	1.6×10^{-2}	2.8×10^{-2}
Curium-248	8.3×10^{-7}	3.4×10^{-2}	5.7×10^{-2}	6.1×10^{-7}	1.4×10^{-2}	2.3×10^{-2}	4.8×10^{-2}	8.0×10^{-2}
Californium-252	6.7×10^{-8}	2.8×10^{-3}	4.6×10^{-3}	3.1×10^{-8}	6.8×10^{-4}	1.1×10^{-3}	3.4×10^{-3}	5.7×10^{-3}

a. Source: Compilation of Tables A-8 and A-9.

b. MTHM = metric tons of heavy metal.

Table A-11. Stainless-steel-clad spent nuclear fuel inventory.[a]

Discharging reactor	Storage location	Assemblies	MTHM[b]
Yankee-Rowe	Yankee-Rowe	76	21
San Onofre 1	San Onofre	395	144
San Onofre 1	Morris, Illinois	270	99
Indian Point 1	Indian Point	160	31
LaCrosse	LaCrosse	333	38
Haddam Neck	Haddam Neck	871	360
Haddam Neck	Morris, Illinois	82	34
Totals		**2,187**	**727**

a. Source: Cole (1998b, all).
b. MTHM = metric tons of heavy metal.

Table A-12. Elemental distribution of typical pressurized-water reactor fuel.[a]

Element	Grams per assembly[b]	Percent total[c]	Element	Grams per assembly[b]	Percent total[c]
Aluminum	47	0.01	Oxygen	62,000	9.35
Americium	600	0.09	Palladium	790	0.12
Barium	1,200	0.18	Phosphorus	85	0.01
Cadmium	77	0.01	Plutonium	4,600	0.69
Carbon	77	0.01	Praseodymium	610	0.09
Cerium	1,300	0.20	Rhodium	230	0.04
Cesium	1,100	0.17	Rubidium	200	0.03
Chromium	4,300	0.65	Ruthenium	1,200	0.18
Cobalt	38	0.01	Samarium	470	0.07
Europium	72	0.01	Silicon	170	0.03
Gadolinium	81	0.01	Silver	40	0.01
Iodine	130	0.02	Strontium	330	0.05
Iron	12,000	1.85	Technetium	420	0.06
Krypton	190	0.03	Tellurium	270	0.04
Lanthanum	670	0.10	Tin	1,900	0.29
Manganese	330	0.05	Titanium	51	0.01
Molybdenum	2,000	0.31	Uranium	440,000	65.78
Neodymium	2,200	0.33	Xenon	2,900	0.43
Neptunium	330	0.05	Yttrium	250	0.04
Nickel	5,000	0.75	Zirconium	120,000	17.77
Niobium	330	0.05			
Nitrogen	49	0.01	**Totals**	**668,637**	**99.99**

a. Source: DOE (1992, page 1.1-1).
b. To convert grams to ounces, multiply by 0.035274.
c. Table only includes elements that constitute at least 0.01 percent of the total; therefore, the total of the percentage column is slightly less than 100 percent.

A.2.1.5.4 *Thermal Output*

Heat generation rates are available as a function of spent fuel type, enrichment, burnup, and decay time in the Light-Water Reactor Radiological Database, which is an integral part of the *Characteristics Potential Repository Wastes* (DOE 1992, page 1.1-1). Table A-14 lists the thermal profiles for the typical pressurized-water reactor and boiling-water reactor assemblies from the Light-Water Reactor Radiological Database. For the EIS analysis, the typical thermal profile, applied across the proposed inventory, yields a good approximation of the expected thermal load in the repository. Figure A-6 shows these profiles as a function of time.

Table A-13. Elemental distribution of typical boiling-water reactor fuel.[a]

Element	Grams per assembly[b]	Percent total[c]	Element	Grams per assembly[b]	Percent total[c]
Aluminum	31	0.01	Nitrogen	25	0.01
Americium	220	0.07	Oxygen	25,000	7.82
Barium	390	0.12	Palladium	270	0.09
Cadmium	27	0.01	Plutonium	1,500	0.48
Carbon	36	0.01	Praseodymium	200	0.06
Cerium	430	0.14	Rhodium	79	0.03
Cesium	390	0.12	Rubidium	64	0.02
Chromium	1,900	0.60	Ruthenium	410	0.13
Cobalt	26	0.01	Samarium	160	0.05
Europium	24	0.01	Silicon	80	0.03
Gadolinium	310	0.10	Strontium	110	0.03
Iodine	43	0.01	Technetium	140	0.04
Iron	5,100	1.63	Tellurium	91	0.03
Krypton	62	0.02	Tin	1,600	0.50
Lanthanum	220	0.07	Titanium	83	0.03
Manganese	160	0.05	Uranium	170,000	55.35
Molybdenum	630	0.20	Xenon	950	0.30
Neodymium	730	0.23	Yttrium	81	0.03
Neptunium	97	0.03	Zirconium	96,000	30.52
Nickel	3,000	0.94			
Niobium	29	0.01	**Totals**	**310,698**	**99.94**

a. Source: DOE (1992, page 1.1-1).
b. To convert grams to ounces, multiply by 0.035274.
c. Table only includes elements that contribute at least 0.01 percent of the total; therefore, the total of the percentage column is slightly less than 100 percent.

Table A-14. Typical assembly thermal profiles.[a]

Years after discharge	Pressurized-water reactor		Boiling-water reactor	
	W/MTHM[b]	W/assembly[c]	W/MTHM	W/assembly[d]
1	10,500	4,800	8,400	1,500
3	3,700	1,700	3,000	550
5	2,200	1,000	1,800	340
10	1,500	670	1,200	220
26	990	450	820	150
30	920	420	770	140
50	670	310	570	100
100	370	170	320	58
300	160	73	140	26
500	120	53	100	19
1,000	66	31	58	11
2,000	35	16	30	5
5,000	22	10	19	3
10,000	16	8	13	3

a. Source: DOE (1992, page 1.1-1).
b. W/MTHM = watts per metric ton of heavy metal; to convert metric tons to tons, multiply by 1.1023.
c. W/assembly = watts per assembly; assumes 0.46 MTHM per assembly.
d. Assumes 0.18 MTHM per assembly.

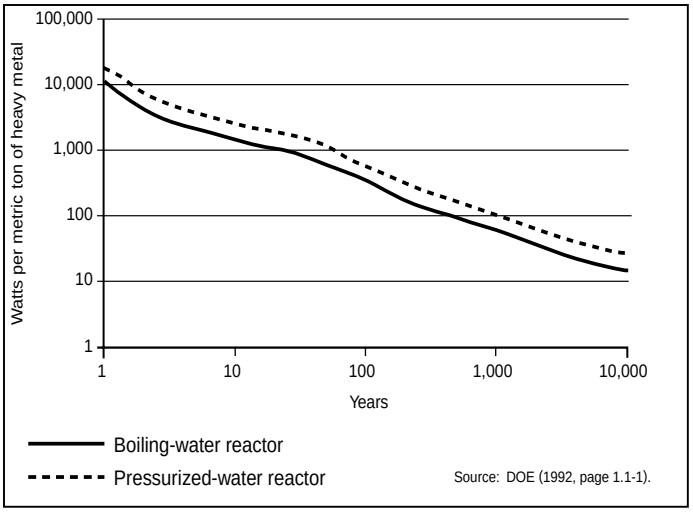


Figure A-6. Typical thermal profiles over time.

A.2.1.5.5 *Physical Parameters*

Table A-15 lists reference characteristics of typical pressurized-water and boiling-water reactor fuel assemblies. These data are from the *Integrated Data Base Report* (DOE 1997b, page 1-8) and reflect characteristics of unirradiated assemblies.

Table A-15. Reference characteristics for unirradiated typical fuel assemblies.[a]

Characteristics[b]	Boiling-water reactor	Pressurized-water reactor
Overall assembly length (meters)	4.5	4.1
Cross section (centimeters)	14×14	21×21
Fuel rod length (meters)	4.1	3.9
Active fuel height (meters)	3.8	3.7
Fuel rod outer diameter (centimeters)	1.3	0.95
Fuel rod array	8×8	17×17
Fuel rods per assembly	63	264
Assembly total weight (kilograms)	320	660
Uranium per assembly (kilograms)	180	460
Uranium oxide per assembly (kilograms)	210	520
Zirconium alloy per assembly (kilograms)	100[c]	110[d]
Hardware per assembly (kilograms)	8.6[e]	26[f]
Nominal volume per assembly (cubic meters)	0.086[g]	0.19[g]

a. Source: DOE (1997b, page 1-8).
b. To convert meters to feet, multiply by 3.2808; to convert centimeters to inches, multiply by 0.3937; to convert kilograms to pounds, multiply by 2.2046; to convert cubic meters to cubic feet, multiply by 35.314.
c. Includes zirconium alloy fuel rod spacers and fuel channels.
d. Includes zirconium alloy control rod guide thimbles.
e. Includes stainless-steel tie plates, Inconel springs, and plenum springs.
f. Includes stainless-steel nozzles and Inconel-718 grids.
g. Based on overall outside dimension; includes spacing between the stacked fuel rods of the assembly.

For additional details, the Light-Water Reactor Assembly Database contains individual physical descriptions of the fuel assemblies and fuel pins. The Light-Water Reactor Nonfuel Assembly Hardware Database contains physical and radiological descriptions of nonfuel assembly hardware. These databases are integral parts of the *Characteristics of Potential Repository Wastes* (DOE 1992, Section 2.8).

A.2.2 DOE SPENT NUCLEAR FUEL

A.2.2.1 Background

At present, DOE stores most of its spent nuclear fuel at three primary locations: the Hanford Site in Washington State, the Idaho National Engineering and Environmental Laboratory in Idaho, and the Savannah River Site in South Carolina. Some DOE spent nuclear fuel is stored at the Fort St. Vrain dry storage facility in Colorado. Much smaller quantities remain at other locations (LMIT 1997, all). DOE issued the *Record of Decision – Department of Energy Programmatic Spent Nuclear Fuel Management and Idaho National Engineering Laboratory Environmental Restoration and Waste Management Programs Final Environmental Impact Statement* on June 1, 1995 (DOE 1995b, all) and amended it in March 1996 (DOE 1996, all). The Record of Decision and its amendment specify three primary locations as storage sites for DOE spent nuclear fuel. With the exception of Fort St. Vrain, which will retain its spent nuclear fuel in dry storage, DOE will ship all its spent nuclear fuel from other sites to one of the three primary sites for storage and preparation for ultimate disposition.

During the last four decades, DOE and its predecessor agencies have generated more than 200 varieties of spent nuclear fuel from weapons production, nuclear propulsion, and research missions. A method described by Fillmore (1998, all) allows grouping of these many varieties of spent nuclear fuel into 16 categories for the repository Total System Performance Assessment. The grouping method uses regulatory requirements to identify the parameters that would affect the performance of DOE spent nuclear fuel in the repository and meet analysis needs for the repository License Application. Three fuel parameters (fuel matrix, fuel compound, and cladding condition) would influence repository performance behavior. The grouping methodology presents the characteristics of a select number of fuel types in a category that either bound or represent a particular characteristic of the whole category. Table A-16 lists these spent nuclear fuel categories.

Table A-16 includes sodium-bonded fuel (Category 14); however, DOE is considering a proposal to treat and manage sodium-bonded spent nuclear fuel for disposal. Alternatives being considered include processing and converting some or all of its sodium-bonded fuel to a high-level radioactive waste form before shipment. Section A.2.3, which covers data associated with high-level radioactive waste, includes data on waste produced from potential future treatment of Category 14 spent nuclear fuel (Dirkmaat 1997b, page 7).

A.2.2.2 Sources

The DOE National Spent Fuel Program maintains a spent nuclear fuel data base (LMIT 1997, all). Table A-16 provides a brief description of each of the fuel categories and a typical fuel. Section A.2.2.5.3 provides more detail on the chemical makeup of each category.

A.2.2.3 Present Storage and Generation Status

Table A-17 lists storage locations and inventory information on DOE spent nuclear fuels. During the preparation of the *Department of Energy Programmatic Spent Nuclear Fuel Management and Idaho National Engineering Laboratory Environmental Restoration and Waste Management Programs Final Environmental Impact Statement* (DOE 1995c, all), DOE evaluated and categorized all the materials listed in the table as spent nuclear fuel, in accordance with the definition in the Nuclear Waste Policy Act, as amended.

Table A-16. DOE spent nuclear fuel categories.[a,b]

	DOE SNF category	Typically from	Description of fuel
1.	Uranium metal	N-Reactor	Uranium metal fuel compounds with aluminum or zirconium alloy cladding
2.	Uranium-zirconium	HWCTR	Uranium alloy fuel compounds with zirconium alloy cladding
3.	Uranium-molybdenum	Fermi	Uranium-molybdenum alloy fuel compounds with zirconium alloy cladding
4.	Uranium oxide, intact	Commercial PWR	Uranium oxide fuel compounds with zirconium alloy or stainless-steel cladding in fair to good condition
5.	Uranium oxide, failed/ declad/aluminum clad	TMI core debris	Uranium oxide fuel compounds: (1) without cladding; (2) clad with zirconium alloy, Hastelloy, nickel-chromium, or stainless steel in poor or unknown condition; or (3) nondegraded aluminum clad
6.	Uranium-aluminide	ATR	Uranium-aluminum alloy fuel compounds with aluminum cladding
7.	Uranium-silicide	FRR MTR	Uranium silicide fuel compounds with aluminum cladding
8.	Thorium/uranium carbide, high-integrity	Fort St. Vrain	Thorium/uranium carbide fuel compounds with graphite cladding in good condition
9.	Thorium/uranium carbide, low-integrity	Peach Bottom	Thorium/uranium carbide fuel compounds with graphite cladding in unknown condition
10.	Plutonium/uranium carbide, nongraphite	FFTF carbide	Uranium carbide or plutonium-uranium carbide fuel compounds with or without stainless-steel cladding
11.	Mixed oxide	FFTF oxide	Plutonium/uranium oxide fuel compounds in zirconium alloy, stainless-steel, or unknown cladding
12.	Uranium/thorium oxide	Shippingport LWBR	Uranium/thorium oxide fuel compounds with zirconium alloy or stainless-steel cladding
13.	Uranium-zirconium hydride	TRIGA	Uranium-zirconium hydride fuel compounds with or without Incalloy, stainless-steel, or aluminum cladding
14.	Sodium-bonded	EBR-II driver and blanket, Fermi-I blanket	Uranium and uranium-plutonium metallic alloy with predominantly stainless-steel cladding
15.	Naval fuel	Surface ship/ submarine	Uranium-based with zirconium alloy cladding
16.	Miscellaneous	Not specified	Various fuel compounds with or without zirconium alloy, aluminum, Hastelloy, tantalum, niobium, stainless-steel or unknown cladding

a. Source: Fillmore (1998, all).

b. Abbreviations: SNF = spent nuclear fuel; HWCTR = heavy-water cooled test reactor; PWR = pressurized-water reactor; TMI = Three Mile Island; ATR = Advanced Test Reactor; FRR MTR = foreign research reactor – material test reactor; FFTF = Fast Flux Test Facility; LWBR = light-water breeder reactor; TRIGA = Training Research Isotopes – General Atomic; EBR-II = Experimental Breeder Reactor II.

A.2.2.4 Final Spent Nuclear Fuel Form

For all spent nuclear fuel categories except 14, the expected final spent nuclear fuel form does not differ from the current or planned storage form. Before its disposal in the repository, candidate material would be in compliance with approved acceptance criteria.

DOE has prepared an EIS at the Savannah River Site (DOE 1998d, all) to evaluate potential treatment alternatives for spent nuclear fuel and its ultimate disposal in the repository. The products of any proposed treatment of the Savannah River Site aluminum-based fuels are adequately represented by the

Table A-17. National Spent Nuclear Fuel Database projection of DOE spent nuclear fuel locations and inventories to 2035.[a,b]

	Fuel category and name	Storage Site	No. of units[c]	Mass (kilograms)[d]	Volume (cubic meters)[e]	Fissile mass (kilograms)	Equivalent uranium mass (kilograms)	MTHM
1.	Uranium metal[f]	INEEL	85	4,500	0.7	13	1,700	1.7
		Hanford	100,000	2,160,000	200	25,000	2,100,000	2100
		SRS	350	120,000	18	110	17,000	17
		Totals	*100,435*	*2,284,500*	*218.7*	*25,123*	*2,118,700*	*2119*
2.	Uranium-zirconium	INEEL	69	120	0.7	34	40	0.04
3.	Uranium-molybdenum	INEEL	29,000	4,600	0.3	970	3,800	3.8
4.	Uranium oxide, intact	INEEL	14,000	150,000	41	2,200	80,000	80
		Hanford	87	44,000	11	240	18,000	18
		Totals	*14,087*	*194,000*	*52*	*2,440*	*98,000*	*99*
5.	Uranium oxide, failed/declad/aluminum clad	INEEL	2,000	340,000	140	2,200	83,000	84
		Hanford	13	270	4.2	4	160	0.2
		SRS	7,600	58,000	96	2,600	3,200	3.2
		Totals	*9,613*	*398,270*	*240.2*	*4,804*	*86,360*	*87*
6.	Uranium-aluminide	SRS	18,000	130,000	150	6,000	8,800	8.7
7.	Uranium-silicide	SRS	7,400	47,000	53	1,200	12,000	12
8.	Thorium/uranium carbide, high-integrity	FSV	1,500	190,000	130	640	820	15
		INEEL	1,600	130,000	82	350	440	9.9
		Totals	*3,100*	*320,000*	*212*	*990*	*1,260*	*25*
9.	Thorium/uranium carbide, low-integrity	INEEL	810	55,000	17	180	210	1.7
10.	Plutonium/uranium carbide, nongraphite	INEEL	130	140	0	10	73	0.08
		Hanford	2	330	0.1	11	64	0.07
		Totals	*132*	*470*	*0.1*	*21*	*137*	*0.2*
11.	Mixed oxide	INEEL	2,000	6,100	2.4	240	2,000	2.1
		Hanford	620	110,000	33	2,400	8,000	10
		Totals	*2,620*	*116,100*	*35.1*	*2,640*	*10,000*	*12*
12.	Uranium/thorium oxide	INEEL	260	120,000	18	810	810	50
13.	Uranium-zirconium hydride	INEEL	9,800	33,000	8.1	460	2,000	2
		Hanford	190	660	33	7	36	0.04
		Totals	*9,990*	*33,660*	*8.3*	*467*	*2,036*	*2*
15.	Naval fuel[g,h]	INEEL	300	4,400,000	888	64,000	65,000	65
16.	Miscellaneous	INEEL	1,500	33,000	11	360	5,500	7.7
		Hanford	73	1,700	0.2	30	130	0.2
		SRS	8,800	9,200	8.2	550	2,900	2.9
		Totals	*10,373*	*43,900*	*19.4*	*940*	*8,530*	*11*
Grand totals			**210,000**	**8,150,000**	**1,900**	**110,000**	**2,420,000**	**2,500**

a. Source: Dirkmaat (1998a, all); individual values and totals rounded to two significant figures.
b. Abbreviations: SNF = spent nuclear fuel; INEEL = Idaho National Engineering and Environmental Laboratory; SRS = Savannah River Site; FSV = Fort St. Vrain.
c. Unit is defined as an assembly, bundle of elements, can of material, etc., depending on the particular spent nuclear fuel category.
d. To convert kilograms to pounds, multiply by 2.2046; to convert metric tons to tons, multiply by 1.1023.
e. To convert cubic meters to cubic yards, multiply by 1.3079.
f. N-Reactor fuel is stored in aluminum or stainless-steel cans at the K-East and K-West Basins. The mass listed in this table does not include the storage cans.
g. Information supplied by the Navy (Dirkmaat 1997a, Attachment, page 2).
h. A naval fuel unit consists of a naval dual-purpose canister that contains multiple assemblies.

properties of the present aluminum-based fuel (Categories 6, 7, and part of 5) for this Yucca Mountain EIS. They are bounded by the same total radionuclide inventory, heat generation rates, dissolution rates, and number of canisters. No additional data about the products will be required to ensure that they are represented in the EIS inventory.

A.2.2.5 Spent Nuclear Fuel Characteristics

A.2.2.5.1 *Mass and Volume*

Table A-17 lists total volume, mass, and MTHM for each DOE spent nuclear fuel category from the National Spent Nuclear Fuel Database (LMIT 1997, all).

A.2.2.5.2 *Amount and Nature of Radioactivity*

ORIGEN2 (Oak Ridge Isotope Generation), an accepted computer code for calculating spent nuclear fuel radionuclide inventories, was used to generate activity data for radionuclides in the DOE spent nuclear fuel inventory. The inventory came from the 1997 version of the National Spent Nuclear Fuel Database (LMIT 1997, all).

Table A-18 lists the activities expressed in terms of curies per handling unit for the radionuclides of interest (uranium, fission products and actinides). The table lists activity estimates decayed to 2030 for all categories except 15. A handling unit for DOE is a spent nuclear fuel canister, while for Category 15 naval fuels, it is a naval dual-purpose canister.

The activity for naval spent nuclear fuel is provided for typical submarine (15a) or surface ship (15b) spent nuclear fuels. Dirkmaat (1997a, Attachment, pages 3 to 5) provided these activities for 5 years after shutdown, which would be the minimum cooling time before naval fuel would reach the repository. The power history assumed operations at power for a full core life. The assumptions about the power history and minimum cooling time conservatively bound the activity for naval fuel that would be emplaced in a monitored geologic repository. In addition, ORIGEN2 was used to calculate the activity associated with activation products in the cladding, which are listed in Table A-18. For completeness, the data also include the activity that would be present in the activated corrosion products deposited on the fuel.

A.2.2.5.3 *Chemical Composition*

This section discusses the chemical compositions of each of the 16 categories of DOE spent nuclear fuel (Dirkmaat 1998a, all).

- *Category 1: Uranium metal.* The fuel in this category consists primarily of uranium metal. N-reactor fuel represents the category because its mass is so large that the performance of the rest of the fuel in the category, even if greatly different from N-Reactor fuel, would not change the overall category performance. The fuel is composed of uranium metal about 1.25 percent enriched in uranium-235, and is clad with a zirconium alloy. Approximately 50 percent of the fuel elements are believed to have failed cladding. This fuel typically has low burnup. Other contributors to this category include the Single Pass Reactor fuel at Hanford and declad Experimental Breeder Reactor-II blanket material at the Savannah River Site.

- *Category 2: Uranium-zirconium.* The fuel in this category consists primarily of a uranium- (91-percent) zirconium alloy. The Heavy Water Components Test Reactor fuel is the representative fuel because it is the largest part of the inventory. This fuel is approximately 85-percent enriched in uranium-235 and is clad with a zirconium alloy.

- *Category 3: Uranium molybdenum.* The fuel in this category consists of uranium- (10 percent)-molybdenum alloy and 25-percent enriched in uranium-235, and is clad with a zirconium alloy. Fermi driver core 1 and 2 are the only fuels in the category. The fuel is currently in an aluminum container. The proposed disposition would include the aluminum container.

Table A-18. Radionuclide activity by DOE spent nuclear fuel category[a] (page 1 of 2).

Storage site[b]	Category[c] 1	2	3	4	5	6	7	8	9	10	11	12	13	15a[d]	15b	16
	Number of handling units															
Hanford	440	0	0	34	1	0	0	0	0	2	324	0	3	0	0	5
INEEL	6	8	70	195	406	0	0	503[e]	60	3	43	71	97	200	100	39
SRS	9	0	0	0	425	750	225	0	0	0	0	0	0	0	0	2
Totals	**455**	**8**	**70**	**229**	**832**	**750**	**225**	**503**	**60**	**5**	**367**	**71**	**100**	**200**	**100**	**46**
Radio-nuclide[f]	Curies per handling unit															
Ac-227	2.2×10^{-5}	4.8×10^{-9}	6.9×10^{-6}	1.7×10^{-4}	1.4×10^{-5}	3.4×10^{-7}	2.3×10^{-7}	0	2.8×10^{-3}	8.9×10^{-9}	1.5×10^{-9}	4.3×10^{-1}	5.6×10^{-8}	1.3×10^{-4}	1.6×10^{-4}	6.8×10^{-7}
Am-241	1.1×10^{3}	3.9×10^{-1}	4.6×10^{-5}	1.6×10^{3}	7.3	3.3	3.6×10^{1}	3.7	2.7	2.4×10^{2}	4.3×10^{2}	8.3×10^{-1}	2.0×10^{-1}	4.9×10^{1}	6.7×10^{1}	1.2×10^{2}
Am-242m	6.6×10^{-2}	1.2×10^{-3}	0	2.6	1.4×10^{-2}	2.3×10^{-3}	1.3×10^{-2}	1.0×10^{-3}	1.4×10^{-3}	4.1×10^{-1}	7.5×10^{-1}	8.7×10^{-3}	2.3×10^{-3}	6.6×10^{-1}	8.5×10^{-1}	1.5×10^{-1}
Am-243	2.8×10^{-1}	3.8×10^{-3}	7.3×10^{-13}	8.3	2.2×10^{-2}	2.5×10^{-3}	3.6×10^{-2}	2.7×10^{-2}	1.3×10^{-3}	6.7×10^{-3}	1.8×10^{-1}	1.7×10^{-3}	2.5×10^{-4}	6.2×10^{-1}	1.1	4.9×10^{-1}
C-14	1.5	8.2×10^{-6}	2.2×10^{-3}	1.0×10^{-1}	1.1×10^{-3}	9.9×10^{-7}	1.8×10^{-5}	2.2×10^{-1}	3.7×10^{-2}	1.5×10^{-5}	9.9×10^{-4}	6.7×10^{-1}	8.5×10^{-2}	2.7×10^{1}	4.6×10^{1}	1.7×10^{-3}
Cf-252	--[f]	--	--	--	--	--	--	--	--	--	--	--	--	2.8×10^{-8}	1.4×10^{-7}	--
Cl-36	0	0	5.6×10^{-6}	3.5×10^{-4}	1.7×10^{-5}	0	0	2.7×10^{-3}	1.1×10^{-3}	0	1.1×10^{-5}	1.5×10^{-2}	2.6×10^{-3}	1.0	1.8	4.2×10^{-6}
Cm-242	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	0	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	$< 7.4\times10^{1}$	$< 7.3\times10^{1}$	$< 7.4\times10^{1}$	1.5	2.2	$< 7.4\times10^{1}$
Cm-243	--	--	--	--	--	--	--	--	--	--	--	--	--	7.4×10^{-1}	2.8×10^{-2}	
Cm-244	8.5	1.6×10^{-1}	6.8×10^{-14}	3.5×10^{2}	9.3×10^{-1}	2.1×10^{-2}	3.0×10^{-1}	8.3×10^{-1}	3.5×10^{-2}	2.8×10^{-1}	7.6	1.6×10^{-1}	6.8×10^{-3}	4.6×10^{1}	9.9×10^{1}	1.9×10^{1}
Cm-245	3.6×10^{-3}	8.0×10^{-6}	1.9×10^{-19}	1.4×10^{-1}	3.8×10^{-4}	1.8×10^{-6}	2.0×10^{-5}	1.4×10^{-4}	4.0×10^{-6}	1.4×10^{-5}	3.1×10^{-3}	3.3×10^{-5}	1.4×10^{-7}	3.8×10^{-3}	9.1×10^{-3}	7.1×10^{-3}
Cm-246	5.3×10^{-4}	5.5×10^{-7}	6.1×10^{-23}	2.4×10^{-2}	6.4×10^{-5}	8.6×10^{-8}	1.5×10^{-6}	6.9×10^{-5}	1.3×10^{-7}	9.7×10^{-7}	5.3×10^{-4}	2.2×10^{-6}	3.9×10^{-9}	6.6×10^{-4}	1.9×10^{-3}	1.2×10^{-3}
Cm-247	--	--	--	--	--	--	--	--	--	--	--	--	--	1.6×10^{-9}	5.1×10^{-9}	--
Cm-248	--	--	--	--	--	--	--	--	--	--	--	--	--	3.1×10^{-9}	1.1×10^{-8}	--
Co-60	1.4×10^{-1}	0	1.1×10^{-2}	1.8×10^{1}	1.6×10^{-12}	1.2×10^{-11}	2.0×10^{-10}	0	2.5×10^{-2}	1.8	1.4	4.3	1.8×10^{-1}	9.0×10^{2}	1.6×10^{3}	7.6×10^{-4}
Cs-134	2.7×10^{-1}	4.6×10^{-2}	1.9×10^{-8}	9.6×10^{-2}	8.3×10^{-3}	1.7×10^{-1}	3.7×10^{-1}	7.6×10^{-3}	3.6×10^{-7}	3.4×10^{-2}	7.5×10^{-3}	6.0×10^{-3}	3.3×10^{-4}	3.1×10^{1}	5.5×10^{1}	5.7×10^{-1}
Cs-135	1.8×10^{-1}	7.7×10^{-3}	4.5×10^{-3}	1.8×10^{-1}	2.9×10^{-2}	2.8×10^{-2}	1.9×10^{-2}	1.7×10^{-2}	2.6×10^{-2}	1.4×10^{-2}	3.2×10^{-3}	2.0×10^{-1}	3.2×10^{-2}	3.9	4.7	1.4×10^{-1}
Cs-137	2.0×10^{4}	7.4×10^{3}	0	2.9×10^{4}	3.6×10^{3}	3.8×10^{3}	8.1×10^{3}	2.4×10^{3}	1.9×10^{3}	1.5×10^{4}	4.0×10^{3}	2.5×10^{3}	3.1×10^{3}	4.4×10^{5}	5.5×10^{5}	8.7×10^{4}
H-3	2.3×10^{1}	4.4	8.6×10^{-2}	3.6×10^{1}	1.3	5.9×10^{-1}	1.3×10^{1}	2.0	1.5	7.3	2.8	2.3×10^{1}	9.6×10^{-1}	1.5×10^{3}	1.8×10^{3}	1.3×10^{1}
I-129	1.6×10^{-2}	1.6×10^{-3}	1.2×10^{-4}	1.8×10^{-2}	7.5×10^{-4}	1.8×10^{-3}	3.8×10^{-3}	2.1×10^{-3}	7.3×10^{-4}	2.9×10^{-3}	3.6×10^{-4}	1.1×10^{-2}	7.2×10^{-4}	1.1×10^{-1}	1.4×10^{-1}	2.3×10^{-2}
Kr-85	3.6×10^{2}	9.3×10^{1}	7.7×10^{-1}	3.1×10^{2}	2.7×10^{1}	1.3×10^{2}	2.6×10^{2}	6.0×10^{1}	7.2	4.8×10^{1}	2.4×10^{1}	6.2×10^{2}	1.7×10^{1}	3.8×10^{4}	4.7×10^{4}	4.2×10^{2}
Nb-93m	8.0×10^{-1}	8.7×10^{-3}	4.6×10^{-3}	6.7×10^{-1}	1.1×10^{-2}	1.6×10^{-2}	3.1×10^{-2}	9.2×10^{-3}	4.6×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	3.1×10^{-1}	7.1×10^{-3}	8.5	1.3×10^{1}	1.7×10^{-1}
Nb-94	5.7×10^{-6}	1.6×10^{-6}	8.4×10^{-4}	7.3×10^{-3}	4.2×10^{-5}	3.1×10^{-6}	7.4×10^{-6}	1.3×10^{-4}	4.9×10^{-4}	2.9×10^{-6}	1.9×10^{-5}	1.6×10^{-2}	4.6×10^{-3}	2.1×10^{2}	3.7×10^{2}	3.5×10^{-5}
Ni-59	8.2×10^{-2}	0	6.9×10^{-3}	9.4×10^{-2}	2.3×10^{-4}	0	0	1.7×10^{-2}	1.5×10^{-3}	0	2.1×10^{-3}	5.1×10^{-2}	5.0×10^{-1}	1.2	2.0	8.2×10^{-4}
Ni-63	7.7	0	1.4×10^{-1}	3.0×10^{2}	2.5×10^{-2}	2.3×10^{-22}	0	4.1×10^{-1}	1.5×10^{-1}	5.0	8.7	6.2	6.2×10^{1}	1.3×10^{2}	2.3×10^{2}	1.0×10^{-1}
Np-237	1.7×10^{-1}	2.0×10^{-2}	3.3×10^{-4}	1.8×10^{-1}	3.1×10^{-3}	1.2×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	7.4×10^{-3}	3.7×10^{-2}	6.5×10^{-3}	7.1×10^{-4}	1.9×10^{-3}	2.9	4.0	2.4×10^{-1}
Pa-231	5.8×10^{-5}	2.3×10^{-7}	2.0×10^{-5}	3.0×10^{-4}	2.6×10^{-5}	4.2×10^{-6}	2.8×10^{-6}	1.9×10^{-2}	4.8×10^{-3}	4.1×10^{-7}	1.2×10^{-7}	1.1	9.0×10^{-7}	6.4×10^{-4}	7.9×10^{-4}	1.0×10^{-5}
Pb-210	3.2×10^{-10}	8.6×10^{-13}	1.4×10^{-10}	9.0×10^{-8}	5.2×10^{-9}	2.1×10^{-11}	1.2×10^{-11}	4.6×10^{-6}	2.6×10^{-7}	1.5×10^{-12}	3.1×10^{-10}	7.8×10^{-5}	1.4×10^{-12}	7.6×10^{-7}	9×10^{-7}	7.510^{-10}

Table A-18. Radionuclide activity by DOE spent nuclear fuel category[a] (page 2 of 2).

Radio-nuclide[f]	Category[b] 1	2	3	4	5	6	7	8	9	10	11	12	13	15a[c]	15b	16
	Curies per handling unit															
Pd-107	3.3×10^{-2}	1.1×10^{-3}	1.3×10^{-4}	4.8×10^{-2}	8.3×10^{-4}	9.3×10^{-4}	3.5×10^{-3}	8.7×10^{-4}	4.8×10^{-4}	2.0×10^{-3}	1.0×10^{-3}	2.4×10^{-3}	6.0×10^{-4}	7.9×10^{-2}	9.9×10^{-2}	1.8×10^{-2}
Pu-238	2.5×10^{2}	4.3×10^{1}	1.7×10^{-2}	1.2×10^{3}	5.8	1.7×10^{1}	2.8×10^{1}	8.1×10^{1}	1.8×10^{1}	1.1×10^{2}	7.9×10^{1}	2.8	2.1	1.4×10^{4}	2.3×10^{4}	5.3×10^{2}
Pu-239	5.1×10^{2}	1.1	2.0	1.5×10^{2}	1.3×10^{1}	2.4	2.2×10^{1}	2.3×10^{-1}	4.1×10^{-1}	1.9×10^{2}	3.2×10^{2}	1.8×10^{-1}	4.5	1.3×10^{1}	1.8×10^{1}	5.2×10^{1}
Pu-240	3.0×10^{2}	6.1×10^{-1}	6.1×10^{-3}	2.4×10^{2}	4.4	1.2	1.6×10^{1}	3.8×10^{-1}	3.2×10^{-1}	1.6×10^{2}	2.8×10^{2}	1.0×10-1	1.8	9.9	1.4×10^{1}	3.7×10^{1}
Pu-241	3.8×10^{3}	2.1×10^{2}	6.0×10^{-4}	1.4×10^{4}	2.9×10^{2}	6.3×10^{1}	7.0×10^{2}	0	3.0×10^{1}	1.7×10^{3}	2.6×10^{3}	2.4×10^{1}	1.3×10^{2}	4.2×10^{3}	5.9×10^{3}	3.5×10^{3}
Pu-242	1.6×10^{-1}	9.2×10^{-4}	3.8×10^{-11}	9.1×10^{-1}	3.0×10^{-3}	9.9×10^{-4}	1.6×10^{-2}	0	4.2×10^{-4}	1.6×10^{-3}	2.0×10^{-2}	2.3×10^{-4}	2.5×10^{-4}	5.7×10^{-2}	9.0×10^{-2}	7.0×10^{-2}
Ra-226	4.6×10^{-6}	2.2×10^{-12}	6.5×10^{-10}	2.6×10^{-7}	2.0×10^{-8}	3.8×10^{-10}	2.3×10^{-10}	4.9×10^{-6}	9.3×10^{-7}	2.3×10^{-9}	5.3×10^{-9}	4.5×10^{-5}	2.3×10^{-12}	5.6×10^{-6}	6.3×10^{-6}	4.1×10^{-9}
Ra-228	3.7×10^{-10}	1.2×10^{-13}	4.0×10^{-9}	1.3×10^{-4}	1.1×10^{-5}	7.3×10^{-13}	1.1×10^{-12}	6.5×10^{-3}	2.4×10^{-3}	6.9×10^{-13}	2.0×10^{-11}	7.1×10^{-2}	3.5×10^{-9}	3.0×10^{-7}	5.3×10^{-7}	1.5×10^{-11}
Rh-102	--	--	--	--	--	--	--	--	--	--	--	--	--	1.1	1.5	--
Ru-106	3.1×10^{-5}	6.3×10^{-7}	3.1×10^{-15}	3.9×10^{-7}	1.2×10^{-6}	1.3×10^{-5}	4.2×10^{-5}	3.2×10^{-9}	3.0×10^{-15}	2.6×10^{-6}	3.1×10^{-8}	2.2×10^{-10}	1.5×10^{-9}	4.2	7.1	5.7×10^{-5}
Se-79	2.6×10^{-1}	3.0×10^{-2}	1.7×10^{-3}	1.9×10^{-1}	1.6×10^{-2}	5.0×10^{-2}	1.0×10^{-1}	2.9×10^{-2}	1.4×10^{-2}	5.2×10^{-2}	3.6×10^{-3}	2.5×10^{-1}	1.3×10^{-2}	2.2	2.7	4.7×10^{-1}
Sm-151	3.3×10^{2}	2.7×10^{1}	6.9	5.3×10^{2}	2.5×10^{1}	4.2×10^{1}	3.4×10^{1}	4.5×10^{1}	2.6×10^{1}	1.8×10^{2}	2.4×10^{2}	9.1×10^{1}	2.4×10^{1}	1.2×10^{3}	1.3×10^{3}	3.8×10^{2}
Sn-126	3.5×10^{-1}	2.6×10^{-2}	3.8×10^{-3}	2.4×10^{-1}	1.2×10^{-2}	1.7×10^{-2}	4.1×10^{-2}	1.4×10^{-2}	1.2×10^{-2}	4.7×10^{-2}	4.8×10^{-3}	2.8×10^{-1}	1.2×10^{-2}	1.9	2.4	3.3×10^{-1}
Sr-90	1.6×10^{4}	7.1×10^{3}	0	2.1×10^{4}	3.2×10^{3}	3.7×10^{3}	7.6×10^{3}	2.3×10^{3}	1.8×10^{3}	1.3×10^{4}	1.6×10^{3}	2.6×10^{3}	2.9×10^{3}	4.2×10^{5}	5.2×10^{5}	8.3×10^{4}
Tc-99	7.7	9.9×10^{-1}	4.5×10^{-2}	6.6	4.2×10^{-1}	1.0	2.2	7.4×10^{-1}	4.1×10^{-1}	1.8	1.3×10^{-1}	2.3	4.3×10^{-1}	6.7×10^{1}	8.2×10^{1}	1.4×10^{1}
Th-229	3.9×10^{-8}	1.1×10^{-10}	2.4×10^{-9}	4.0×10^{-4}	3.2×10^{-5}	2.2×10^{-9}	1.2×10^{-9}	2.8×10^{-2}	6.8×10^{-3}	2.5×10^{-10}	1.7×10^{-9}	1.8×10^{-1}	1.2×10^{-9}	6.1×10^{-6}	9.9×10^{-6}	8.7×10^{-9}
Th-230	4.4×10^{-6}	8.6×10^{-9}	1.2×10^{-7}	3.7×10^{-5}	2.9×10^{-6}	1.8×10^{-7}	1.2×10^{-7}	1.9×10^{-3}	1.3×10^{-4}	5.1×10^{-7}	1.2×10^{-6}	6.9×10^{-3}	3.9×10^{-9}	1.9×10^{-3}	2.1×10^{-3}	1.2×10^{-6}
Th-232	5.1×10^{-10}	2.0×10^{-12}	4.3×10^{-9}	1.4×10^{-4}	1.2×10^{-5}	1.9×10^{-11}	3.0×10^{-11}	5.1×10^{-3}	2.5×10^{-3}	4.4×10^{-12}	5.5×10^{-11}	8.4×10^{-2}	1.0×10^{-8}	3.8×10^{-7}	6.6×10^{-7}	9.8×10^{-11}
U-232	9.9×10^{-5}	3.5×10^{-5}	1.9×10^{-6}	0	2.2×10^{-5}	1.7×10^{-4}	1.4×10^{-4}	2.3	2.4×10^{-1}	0	0	7.1×10^{2}	2.4×10^{-5}	3.2×10^{-1}	4.9×10^{-1}	3.5×10^{-4}
U-233	2.5×10^{-5}	9.1×10^{-7}	9.9×10^{-7}	1.6×10^{-1}	1.2×10^{-2}	2.6×10^{-6}	1.8×10^{-6}	6.9	2.6	1.7×10^{-6}	9.3×10^{-7}	1.2×10^{2}	5.6×10^{-6}	1.8×10^{-3}	3.0×10^{-3}	1.6×10^{-5}
U-234	2.0	8.6×10^{-4}	5.0×10^{-4}	1.7×10^{-1}	1.1×10^{-2}	2.2×10^{-3}	1.8×10^{-3}	5.6×10^{-1}	4.4×10^{-1}	4.9×10^{-3}	8.0×10^{-3}	5.9	2.1×10^{-4}	1.7×10^{1}	1.8×10^{1}	1.8×10^{-2}
U-235	8.4×10^{-2}	8.2×10^{-3}	3.2×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	1.8×10^{-2}	1.3×10^{-2}	2.2×10^{-3}	6.8×10^{-3}	1.5×10^{-2}	2.2×10^{-4}	4.0×10^{-4}	9.9×10^{-3}	2.6×10^{-1}	2.5×10^{-1}	1.2×10^{-1}
U-236	3.3×10^{-1}	3.4×10^{-2}	1.7	1.4×10^{-1}	1.2×10^{-2}	3.7×10^{-2}	5.9×10^{-2}	2.1×10^{-2}	1.7×10^{-2}	6.0×10^{-2}	4.1×10^{-3}	8.1×10^{-4}	1.3×10^{-2}	3.3	4.0	4.4×10^{-1}
U-238	1.6	1.5×10^{-4}	1.4×10^{-2}	1.3×10^{-1}	3.4×10^{-2}	8.9×10^{-4}	1.6×10^{-2}	5.4×10^{-5}	7.1×10^{-5}	2.7×10^{-4}	2.7×10^{-3}	1.3×10^{-5}	5.8×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	2.4×10^{-2}
Zr-93	1.0	1.5×10^{-1}	6.7×10^{-3}	9.1×10^{-1}	5.0×10^{-2}	1.0×10^{-1}	2.1×10^{-1}	1.1	6.4×10^{-2}	2.7×10^{-1}	1.7×10^{-2}	5.7×10^{-1}	7.8×10^{-2}	1.8×10^{1}	2.7×10^{1}	1.9

a. Source: Dirkmaat (1998b, all); values are rounded to two significant figures.
b. INEEL = Idaho National Engineering and Environmental Laboratory; SRS = Savannah River Site.
c. Categories 1-13 and 16 decayed to 2030. Category 15 cooled for 5 years.
d. 15a = naval submarine fuel; 15b = naval surface ship fuel.
e. Includes 334 canisters from Fort St. Vrain.
f. -- = not found in appreciable quantities.

- *Category 4: Uranium oxide, intact.* The fuel in this category consists of uranium oxide that has been formed into pellets or plates and clad with a corrosion-resistant material. Commercial fuel is the representative fuel for this category because it is a large part of the inventory. The fuel is made of uranium oxide, some of which is highly enriched in uranium-235 and some of which is low enriched in uranium-235. The fuel elements are clad with a zirconium alloy.

- *Category 5: Uranium oxide, failed/declad/aluminum clad.* The fuel in this category is chemically similar to the fuels in Category 4, except accident or destructive examination has disrupted it. The failed fuel from Three Mile Island Reactor 2 represents this category because it comprises 96 percent of the total MTHM of the category. The Three Mile Island Reactor 2 fuel is melted uranium oxide. The accident greatly disrupted the cladding. Other fuel in this category is declad or has a large amount of cladding damage. Approximately 4 percent consists of intact aluminum clad fuel included in this category because the aluminum cladding is less corrosion resistant than Category 4 cladding material.

- *Category 6: Uranium-aluminide.* This category consists of fuel with a uranium-aluminum compound dispersed in a continuous aluminum metal phase. The fuel is clad with an aluminum alloy. The uranium-235 enrichment varies from 10 to 93 percent.

- *Category 7: Uranium-silicide.* The fuel in this category is a uranium-silicide compound dispersed in a continuous aluminum metal phase. The fuel is clad with an aluminum alloy. The uranium-235 enrichment varies from 8 to 93 percent, but most are less than 20 percent.

- *Category 8: Thorium/uranium carbide, high-integrity.* This category consists of fuels with thorium carbide or uranium carbide formed into particles with a high-integrity coating. Fort St. Vrain Reactor fuel represents the category because it makes up 95 percent of the mass of the category. This fuel is uranium carbide and thorium carbide formed into particles and coated with layers of pyrolytic carbon and silicon carbide. The particles are bonded in a carbonaceous matrix material and emplaced in a graphite block. The fuel was made with uranium enriched to 93 percent in uranium-235. The thorium was used to generate fissile uranium-233 during irradiation. Some fuel does not have a silicon carbide coating, but its effect on the category is very small. Less than 1 percent of the fuel particles are breached.

- *Category 9: Thorium/uranium carbide, low-integrity.* This category consists of fuels with uranium carbide or thorium carbide made into particles with a coating of an earlier design than that described for Category 8. Peach Bottom Unit 1, Core 1 is the only fuel in this category. This fuel is chemically similar to Category 8 fuel except 60 percent of the particle coating is breached. Peach Bottom Unit 1, Core 2 is included in Category 8 because its fuel particles are basically intact and are more rugged than the Peach Bottom Unit 1, Core 1 particles.

- *Category 10: Plutonium/uranium carbide, nongraphite.* This category consists of fuel that contains uranium carbide. Much of it also contains plutonium carbide. Fast Flux Test Facility carbide assemblies represent this category because they make up 70 percent of the category and contain both uranium and plutonium. The Fast Flux Test Facility carbide fuel was constructed from uncoated uranium and plutonium carbide spheres that were loaded directly into the fuel pins, or pressed into pellets that were loaded into the pins. The pins are clad with stainless steel.

- *Category 11: Mixed oxide.* This category consists of fuels constructed of both uranium oxide and plutonium oxide. The Fast Flux Test Facility mixed-oxide test assembly is the representative fuel because it comprises more than 80 percent of the category. The fuels are a combination of uranium oxide and plutonium oxide pressed into pellets and clad with stainless steel or a zirconium alloy. The

uranium-235 enrichment is low, but the fissile contribution of the plutonium raises the effective enrichment to 15 percent.

- *Category 12: Uranium/thorium oxide.* This category consists of fuels constructed of uranium oxide and thorium oxide. Shippingport light-water breeder reactor fuel is the representative fuel because it comprises more than 75 percent of the inventory. The Shippingport light-water breeder reactor fuel is made of uranium-233, and the irradiation of the thorium produces more uranium-233. The mixture is pressed into pellets and clad with a zirconium alloy.

- *Category 13: Uranium-zirconium hydride.* This category consists of fuels made of uranium-zirconium hydride. Training Research Isotopes-General Atomic fuels comprise more than 90 percent of the mass of this category. The fuel is made of uranium-zirconium hydride formed into rods and clad primarily with stainless steel or aluminum. The uranium is enriched as high as 90 percent in uranium-235, but most is less than 20 percent enriched.

- *Category 14: Sodium-bonded.* For purposes of analysis in this EIS, it is assumed that all Category 14 fuels would be treated during the proposed electrometallurgical treatment that would result in high-level radioactive waste. The chemical composition of the resulting high-level radioactive waste is described in Section A.2.3. Category 14 is included here for completeness.

- *Category 15: Naval fuel.* Naval nuclear fuel is highly robust and designed to operate in a high-temperature, high-pressure environment for many years. This fuel is highly enriched (93 to 97 percent) in uranium-235. In addition, to ensure that the design will be capable of withstanding battle shock loads, the naval fuel material is surrounded by large amounts of zirconium alloy (Beckett 1998, Attachment 2).

  DOE plans to emplace approximately 300 canisters of naval spent nuclear fuel in the Yucca Mountain repository. There are several different designs for naval nuclear fuel, but all designs employ similar materials and mechanical arrangements. The total weight of the fuel assemblies in a canister of a typical submarine spent reactor fuel, which is representative of the chemical composition of naval spent nuclear fuel, would be 11,000 to 13,000 kilograms (24,000 to 29,000 pounds). Of this total, less than 500 kilograms (1,100 pounds) would be uranium. Approximately 1,000 to 2,000 kilograms (2,200 to 4,400 pounds) of the total weight of these fuel assemblies is from hafnium in the poison devices (primarily control rods) permanently affixed to the fuel assemblies (Beckett 1998, Attachment 2).

  There would be approximately 9,000 to 12,000 kilograms (20,000 to 26,500 pounds) of zirconium alloy in the fuel structure in the typical canister. The typical chemical composition of zirconium alloy is approximately 98 percent zirconium, 1.5 percent tin, 0.2 percent iron, and 0.1 percent chromium (Beckett 1998, Attachment 2).

  The small remainder of the fuel mass in a typical canister of naval submarine spent nuclear fuel [less than 500 kilograms (1,100 pounds)] would consist of small amounts of such metals and nonmetals as fission products and oxides (Beckett 1998, Attachment 2).

- *Category 16: Miscellaneous.* This category consists of the fuels that do not fit into the previous 15 categories. The largest amount of this fuel, as measured in MTHM, is uranium metal or alloy. The other two primary contributors are uranium alloy and uranium-thorium alloy. These three fuel types make up more than 80 percent of the MTHM in the category. It is conservative to treat the total category as uranium metal. Other chemical compounds included in this category include uranium

oxide, uranium nitride, uranium alloys, plutonium oxide, plutonium nitride, plutonium alloys, and thorium oxide.

Table A-19 lists the primary materials of construction and chemical composition for each category.

A.2.2.5.4 *Thermal Output*

Table A-20 lists the maximum heat generation per handling unit for each spent nuclear fuel category (Dirkmaat 1997a, Attachment, pages 74 to 77; Dirkmaat 1998b, all). The category 15 (naval fuel) thermal data used the best estimate radionuclide content from Dirkmaat (1997a, Attachment, pages 74 to 77) at a minimum cooling time of 5 years.

A.2.2.5.5 *Quantity of Spent Nuclear Fuel Per Canister*

Table A-21 lists the projected number of canisters required for each site and category. The amount of fuel per canister would vary widely among categories and would depend on a variety of parameters. The average mass of submarine spent nuclear fuel in a short naval dual-purpose canister would be approximately 13 metric tons (14 tons) with an associated volume of 2.7 cubic meters (95 cubic feet). Surface ship spent nuclear fuel in a long naval dual-purpose canister would have an average mass of approximately 18 metric tons (20 tons) and a volume of 3.5 cubic meters (124 cubic feet) (Dirkmaat 1997a, Attachment, pages 86 to 88).

A.2.2.5.6 *Spent Nuclear Fuel Canister Parameters*

The Idaho National Engineering and Environmental Laboratory would use a combination of 46- and 61-centimeter (18- and 24-inch)-diameter stainless-steel canisters for spent nuclear fuel disposition. The Savannah River Site would use 18-inch canisters, and Hanford would use 64-centimeter (25.3-inch) multicanister overpacks and 18-inch canisters. Table A-21 lists the specific number of canisters per site. Detailed canister design specifications for the standard 18- and 24-inch canisters are contained in DOE (1998c, all). Specifications for the Hanford multicanister overpacks are in Parsons (1999, all).

There are two conceptual dual-purpose canister designs for naval fuel: one with a length of 539 centimeters (212 inches) and one with a length of 475 centimeters (187 inches). Both canisters would have a maximum diameter of 169 centimeters (67 inches) (Dirkmaat 1997a, Attachment, pages 86 to 88). Table A-22 summarizes the preliminary design information.

For both designs, the shield plug, shear ring, and outer seal plate would be welded to the canister shell after the fuel baskets were loaded in the canister. The shield plug, shear ring, and welds, along with the canister shell and bottom plug, would form the containment boundary for the disposable container. The shell, inner cover, and outer cover material for the two canisters would be low-carbon austenitic stainless steel or stabilized austenitic stainless steel. Shield plug material for either canister would be stainless steel or another high-density material sheathed in stainless steel (Dirkmaat 1997a, Attachment, pages 86 to 88).

A.2.3 HIGH-LEVEL RADIOACTIVE WASTE

High-level radioactive waste is the highly radioactive material resulting from the reprocessing of spent nuclear fuel. DOE stores high-level radioactive waste at the Hanford Site, the Savannah River Site, and the Idaho National Engineering and Environmental Laboratory. Between 1966 and 1972, commercial chemical reprocessing operations at the Nuclear Fuel Services plant near West Valley, New York, generated a small amount of high-level radioactive waste at a site presently owned by the New York State

Table A-19. Chemical composition of DOE spent nuclear fuel by category (kilograms).[a,b]

	Category														
Fuel	1	2	3	4	5	6	7	8	9	10	11	12	13	15	16
Components															
Uranium	2,120,000	40	3,800	98,000	87,000	8,800	12,000	1,300	210	140	9,900	810	2,000	65,000	8,500
Aluminum	1,700	(c)				18,000	4,200								
Molybdenum			380										9		
Zirconium	140	440		7,500									23,000		
Thorium								27,000	1,500			48,000			2,200
Plutonium										16	2,400				8
Silicon	260						880								
Silicon carbide								53,000							
Carbon	1,200			30				220,000	53,000				1,700		
Cladding and structure															
Aluminum	100		640		18,000	64,000	52,000						11,000		500
Stainless steel				11,000	3,000				8,000	320	2,400	31,000	17,000		20,000
Zirconium alloy	160,000	70	280	64,000	58,000						500	12,000	100	3,600,000	100
Inconel				1,000	1,700										
Container															
Stainless steel	2,640,000	5,600	50,000	165,000	750,000	900,000	270,000	500,000	42,000	3,500	260,000	50,000	70,000	9,900,000	31,000
Aluminum			660		10,000										
Other															
Concrete					30,000[d]										
Boron									29						
Silver					1,100										
Cadmium					34										
Indium					280										
Magnesium									430						
Nickel	210														
Rhodium									30						
Ruthenium									30						
Samarium													67		
Gadolinium					530	950	23								
Hafnium														600,000	

a. Source: Dirkmaat (1998a, all); values are rounded to two significant figures.
b. To convert kilograms to pounds, multiply by 2.2046.
c. Blanks indicate none or less than reportable quantities.
d. Low density converters were added to canisters of Three Mile Island Unit 2 fuel and would remain when shipped to the repository.

Table A-20. Maximum heat generation for DOE spent nuclear fuel (watts per handling unit).[a,b]

Category and fuel type	Maximum heat generation
1. Uranium metal	18
2. Uranium zirconium	90
3. Uranium molybdenum	4
4. Intact uranium oxide	1,000
5. Failed/declad/aluminum clad uranium oxide	800
6. Uranium aluminide	480
7. Uranium silicide	1,400
8. High-integrity thorium/uranium carbide	250
9. Low-integrity thorium/uranium carbide	37
10. Nongraphite plutonium/uranium carbide	1,800
11. Mixed oxide	1,800
12. Thorium/uranium oxide	120
13. Uranium zirconium hydride	100
14. Sodium-bonded	N/A[c]
15. Naval fuel	4,250
16. Miscellaneous	1,000

a. Sources: Dirkmaat (1997a, Attachment, pages 74 to 77; Dirkmaat 1998b, all).
b. Handling unit is a canister or naval dual purpose canister.
c. N/A = not applicable. Assumed to be treated and therefore part of high-level radioactive waste inventory (see Section A.2.2.1).

Table A-21. Required number of canisters for disposal of DOE spent nuclear fuel.[a,b]

	Hanford		INEEL		SRS	Naval	
Category	18-inch	25.3-inch	18-inch	24-inch	18-inch	Short DPC[c]	Long DPC
1		440	6		9		
2			8				
3			70				
4	14	20	179	16			
5	1		406		425		
6					750		
7					225		
8			503[d]				
9			60				
10	2		3				
11	324		43				
12			24	47			
13	3		97				
14[e]							
15						200	100
16	5		39		2		
Totals	**349**	**460**	**1,438**	**63**	**1,411**	**200**	**100**

a. Sources: Dirkmaat (1997b, Attachment, page 2); Dirkmaat (1998a, all).
b. INEEL = Idaho National Engineering and Environmental Laboratory; SRS = Savannah River Site.
c. Naval dual-purpose canister.
d. Includes 334 canisters from Fort St. Vrain.
e. Assumed to be treated and therefore part of high-level radioactive waste inventory (see Section A.2.2.1).

Energy Research and Development Authority. These operations ceased after 1972. In 1980, Congress passed the West Valley Demonstration Project Act, which authorizes DOE to conduct, with the Research and Development Authority, a demonstration of solidification of high-level radioactive waste for disposal and the decontamination and decommissioning of demonstration facilities(DOE 1992, Chapter 3). This

Table A-22. Preliminary naval dual-purpose canister design parameters.[a]

Parameter	Short canister	Long canister
Maximum outside diameter (centimeters)[b,c]	169	169
Maximum outer length (centimeters)	475	539
Minimum loaded weight (metric tons)[d]	27	27
Maximum loaded weight (metric tons)	45	45

a. Source: Dirkmaat (1997a, Attachment, pages 86 to 88).
b. To convert centimeters to inches, multiply by 0.3937.
c. Right circular cylinder.
d. To convert metric tons to tons, multiply by 1.1023.

section addresses defense high-level radioactive waste generated at the DOE sites (Hanford Site, Idaho National Engineering and Environmental Laboratory, and Savannah River Site) and commercial high-level radioactive waste generated at the West Valley Demonstration Project.

A.2.3.1 Background

In 1985, DOE published a report in response to Section 8 of the Nuclear Waste Policy Act (of 1982) that required the Secretary of Energy to recommend to the President whether defense high-level radioactive waste should be disposed of in a geologic repository along with commercial spent nuclear fuel. That report, *An Evaluation of Commercial Repository Capacity for the Disposal of Defense High-Level Waste* (DOE 1985, all), provided the basis, in part, for the President's determination that defense high-level radioactive waste should be disposed of in a geologic repository. Given that determination, DOE decided to allocate 10 percent of the capacity of the first repository for the disposal of DOE spent nuclear fuel (2,333 MTHM) and high-level radioactive waste (4,667 MTHM) (Dreyfuss 1995, all; Lytle 1995, all).

Calculating the MTHM quantity for spent nuclear fuel is straightforward. It is determined by the actual heavy metal content of the spent fuel. However, an equivalence method for determining the MTHM in defense high-level radioactive waste is necessary because almost all of its heavy metal has been removed. A number of alternative methods for determining MTHM equivalence for high-level radioactive waste have been considered over the years. Four of those methods are described in the following paragraphs.

Historical Method. Table 1-1 of the 1985 DOE report provided a method to estimate the MTHM equivalence for high-level radioactive waste based on comparing the radioactive (curie) equivalence of commercial high-level radioactive waste and defense high-level radioactive waste. The method relies on the relative curie content of a hypothetical (in the early 1980s) canister of defense high-level radioactive waste from the Savannah River, Hanford, or Idaho site, and a hypothetical canister of vitrified waste from reprocessing of high-burnup commercial spent nuclear fuel. Based on commercial high-level radioactive waste containing 2.3 MTHM per canister (heavy metal has not been removed from commercial waste) and defense high-level radioactive waste estimated to contain approximately 22 percent of the radioactivity of a canister of commercial high-level radioactive waste, defense high-level radioactive waste was estimated to contain the equivalent of 0.5 MTHM per canister. Since 1985, DOE has used this 0.5 MTHM equivalence per canister of defense high-level radioactive waste in its consideration of the potential impacts of the disposal of defense high-level radioactive waste, including the analysis presented in this EIS. With this method, less than 50 percent of the total inventory of high-level radioactive waste could be disposed of in the repository within the 4,667 MTHM allocation for high-level radioactive waste. There has been no determination of which waste would be shipped to the repository, or the order of shipments.

Spent Nuclear Fuel Reprocessed Method. Another method of determining MTHM equivalence, based on the quantity of spent nuclear fuel reprocessed, would be to consider the MTHM in the high-level radioactive waste to be the same as the MTHM in the spent nuclear fuel before it was reprocessed. Using

this method, less than 5 percent of the total inventory of high-level radioactive waste could be disposed of in the repository within the 4,667 MTHM allocation for high-level radioactive waste.

Total Radioactivity Method. Another method, the total radioactivity method, would establish equivalence based on a comparison of radioactivity inventory (curies) of defense high-level radioactive waste to that of a standard MTHM of commercial spent nuclear fuel. For this equivalence method the standard spent nuclear fuel characteristics are based on pressurized-water reactor fuel with uranium-235 enrichment of 3.11 percent and 39.65 gigawatt-days per MTHM burnup. Using this method, 100 percent of the total inventory of high-level radioactive waste inventory could be disposed of in the repository within the 4,667 MTHM allocation for high-level radioactive waste.

Radiotoxicity Method. Yet another method, the radiotoxicity method, uses a comparison of the relative radiotoxicity of defense high-level radioactive waste to that of a standard MTHM of commercial spent nuclear fuel, and is thus considered an extension of the total radioactivity method. Radiotoxicity compares the inventory of specific radionuclides to a regulatory release limit for that radionuclide, and uses these relationships to develop an overall radiotoxicity index. For this equivalence, the standard spent nuclear fuel characteristics are based on pressurized-water reactor fuel with uranium-235 enrichment of 3.11 percent, 39.65 gigawatt-days per MTHM burnup. Using this method, 100 percent of the total inventory of high-level radioactive waste could be disposed of in the repository within the 4,667 MTHM allocation for high-level radioactive waste.

A recent report (Knecht et al. 1999, all) describes four equivalence calculation methods and notes that, under the Total Radioactivity Method or the Radiotoxicity Method, all DOE high-level radioactive waste could be disposed of under the Proposed Action. Using different equivalence methods would shift the proportion of high-level radioactive waste that could be disposed of between the Proposed Action and Inventory Module 1 analyzed in Chapter 8, but would not change the cumulative impacts analyzed in this EIS. Regardless of the equivalence method used, the EIS analyzes the impacts from disposal of the entire inventory of high-level radioactive waste in inventory Module 1.

A.2.3.2 Sources

A.2.3.2.1 *Hanford Site*

The Hanford high-level radioactive waste materials discussed in this EIS are those in the Tank Waste Remediation System Disposal Program and include tank waste, strontium capsules, and cesium capsules (Picha 1997, Table RL-1). DOE has not declared other miscellaneous materials or waste at Hanford, either existing or forecasted, to be candidate high-level radioactive waste streams. Before shipment to the repository, DOE would vitrify the high-level radioactive waste into a borosilicate glass matrix and pour it into stainless-steel canisters.

A.2.3.2.2 *Idaho National Engineering and Environmental Laboratory*

The Idaho National Engineering and Environmental Laboratory has proposed three different high-level radioactive waste stream matrices for disposal at the proposed Yucca Mountain Repository—glass, ceramic, and metal. The glass matrix waste stream would come from the Idaho Nuclear Technology and Engineering Center and would consist of wastes generated from the treatment of irradiated nuclear fuels. The Argonne National Laboratory-West proposed electrometallurgical treatment of DOE sodium-bonded fuels would generate both ceramic and metallic high-level radioactive waste matrices. DOE is preparing an EIS [DOE/EIS-0287 (Notice of Intent, 62 *FR* 49209, September 19, 1997)] to support decisions on managing the high-level radioactive waste at the Idaho Nuclear Technology and Engineering Center. DOE is preparing a separate EIS on managing sodium-bonded spent nuclear fuel at Argonne National

Laboratory-West and elsewhere, under which electrometallurgical treatment as well as alternative terminologies are being considered [DOE/EIS-0306 (Notice of Intent, 64 *FR* 8553, February 22, 1999)].

A.2.3.2.3 *Savannah River Site*

Savannah River Site high-level radioactive waste consists of wastes generated from the treatment of irradiated nuclear fuels. These wastes include various chemicals, radionuclides, and fission products that DOE maintains in liquid, sludge, and saltcake forms. The Defense Waste Processing Facility at the Savannah River Site mixes the high-level radioactive waste with glass-forming materials, converts it to a durable borosilicate glass waste form, pours it into stainless-steel canisters, and seals the canisters with welded closure plugs (Picha 1997, Attachment 4, page 2).

Another source of high-level radioactive waste at the Savannah River Site is the immobilized plutonium addressed in Section A.2.4.

A.2.3.2.4 *West Valley Demonstration Project*

The West Valley Demonstration Project is responsible for solidifying high-level radioactive waste that remains from the commercial spent nuclear fuel reprocessing plant operated by Nuclear Fuel Services. The Project mixes the high-level radioactive waste with glass-forming materials, converts it to a durable borosilicate glass waste form, pours it into stainless-steel canisters, and seals the canisters with welded closure plugs.

A.2.3.3 Present Status

A.2.3.3.1 *Hanford Site*

The Hanford Site stores high-level radioactive waste in underground carbon-steel tanks. This analysis assumed that before vitrification, strontium and cesium capsules currently stored in water basins at Hanford would be blended with the liquid high-level radioactive waste. To date, Hanford has immobilized no high-level radioactive waste. Before shipping waste to a repository, DOE would vitrify it into an acceptable glass form. DOE has scheduled vitrification to begin in 2007 with an estimated completion in 2028.

A.2.3.3.2 *Idaho National Engineering and Environmental Laboratory*

Most of the high-level radioactive waste at the Idaho Nuclear Technology and Engineering Center (formerly the Idaho Chemical Processing Plant) is in calcined solids (calcine) stored at the Idaho National Engineering and Environmental Laboratory. The calcine, an interim waste form, is in stainless-steel bins in concrete vaults. Before shipment to a repository, DOE proposes to immobilize the high-level radioactive waste in a vitrified (glass) waste form. The Idaho Nuclear Technology and Engineering Center proposes to implement its vitrification program in 2020 and complete it in 2035 (LMIT 1998, pages A-39 to A-42).

As discussed in Section A.2.2.1, DOE is evaluating treatment of sodium-bonded fuels at Argonne National Laboratory-West. If electrometallurgical treatment were to be chosen, DOE would stabilize the high-level radioactive waste generated from the treatment of its sodium-bonded fuel in the Fuel Conditioning Facility and Hot Fuel Examination Facility into ceramic and metal waste forms in the same facilities. The Radioactive Scrap and Waste Facility at Argonne National Laboratory-West would provide interim storage for these waste forms. There are several technologies being considered for waste

treatment (for example, electrometallurgical treatment, melt and dilute, Purex). If a decision was made to implement this proposal, DOE would begin stabilization in 2000.

A.2.3.3.3 *Savannah River Site*

DOE stores high-level radioactive waste in underground tanks in the F- and H-Areas at the Savannah River Site. High-level radioactive waste that has been converted to a borosilicate glass form is stored in the Glass Waste Storage Building in the S-Area. DOE projects completion of the vitrification of the stored high-level radioactive waste by 2022 (Davis and Wells 1997, all).

A.2.3.3.4 *West Valley Demonstration Project*

High-level radioactive waste is stored in underground tanks at the West Valley site. High-level radioactive waste that has been converted into a borosilicate glass waste form is stored in the converted Chemical Process Cell in the Process Building, referred to as the Interim High-Level Radioactive Waste Storage Facility. West Valley plans to complete its vitrification program by the Fall of 2002 (DOE 1992, Chapter 3).

A.2.3.4 Final Waste Form

The final waste form for high-level radioactive waste from the Hanford Site, Savannah River Site, Idaho Nuclear Technology and Engineering Center, and West Valley Demonstration Project would be a vitrified glass matrix in a stainless-steel canister.

The waste forms from Argonne National Laboratory-West could be ceramic and metallic waste matrices depending on decisions to be based on an ongoing EIS. These could be in stainless-steel canisters similar to those used for Savannah River Site and Idaho Nuclear Technology and Engineering Center glass wastes.

A.2.3.5 Waste Characteristics

A.2.3.5.1 *Mass and Volume*

Hanford Site. The estimated volume of borosilicate glass generated by high-level radioactive waste disposal actions at Hanford will be 15,700 cubic meters (554,000 cubic feet); the estimated mass of the glass is 44,000 metric tons (48,500 tons) (Picha 1998a, Attachment 1). The volume calculation assumes that strontium and cesium compounds from capsules currently stored in water basins would be blended with tank wastes before vitrification with no increase in product volume. This volume of glass would require 14,500 canisters, nominally 4.5 meters (15 feet) long with a 0.61-meter (2-foot) diameter (Picha 1998a, Attachment 1).

Idaho National Engineering and Environmental Laboratory. Table A-23 lists the volumes, masses, densities, and estimated number of canisters for the three proposed waste streams.

Savannah River Site. Based on Revision 8 of the High-Level Waste System Plan (Davis and Wells 1997, all), the Savannah River Site would generate an estimated 5,978 canisters of high-level radioactive waste (Picha 1997, Attachment 1). The canisters have a nominal outside diameter of 0.61 meter (2 feet) and a nominal height of 3 meters (10 feet). They would contain a total of approximately 4,240 cubic meters (150,000 cubic feet) of glass. The estimated total mass of high-level radioactive waste for repository disposal would be 11,600 metric tons (12,800 tons) (Picha 1997, Attachment 1). Section A.2.4.5.2.1 addresses the additional high-level radioactive waste canisters that DOE would generate at the

Table A-23. Physical characteristics of high-level radioactive waste at the Idaho National Engineering and Environmental Laboratory.[a,b]

Physical quantities	INTEC glass matrix	ANL-W ceramic matrix	ANL-W metal matrix
Volume (cubic meters)[c]	743	60.0	1.2
Mass (kilograms)[d]	1,860,000	144,000	9,000
Density (kilograms per cubic meter)	2,500	2,400	7,750
Number of canisters [range][e]	1,190	96 [80 - 125]	6 [2 - 10]

a. Sources: Picha (1997, Attachment 1); Goff (1998a, all); Goff (1998b, all).
b. INTEC = Idaho Nuclear Technology and Engineering Center; ANL-W = Argonne National Laboratory-West.
c. To convert cubic meters to cubic yards, multiply by 1.3079.
d. To convert kilograms to pounds, multiply by 2.2046.
e. Canister would be nominally 3 meters (10 feet) by 0.6 meter (2 feet). Canisters would be filled to approximately 0.625 cubic meter (22 cubic feet).

Savannah River Site as a result of immobilizing surplus plutonium. As discussed in that section, 77 additional canisters would be required if the assumed 18 metric tons (20 tons) of plutonium is immobilized. If the entire 50 metric tons (55 tons) of surplus plutonium was immobilized, 210 additional high-level radioactive waste canisters would be required.

West Valley Demonstration Project. The West Valley Demonstration Project will generate between 260 and 300 canisters of high-level radioactive waste. The canisters have a nominal outside diameter of 0.61 meter (2 feet) and a nominal height of 3 meters (10 feet) (Picha 1997, Attachment 1). They will contain approximately 200 cubic meters (7,060 cubic feet) of glass. The estimated total mass of this high-level radioactive waste will be between 540 and 630 metric tons (595 and 694 tons) (Picha 1998c, page 3).

Summary. Table A-24 summarizes the information in the previous paragraphs to provide the total mass and volume projected to be disposed of at the repository.

Table A-24. High-level radioactive waste mass and volume summary.

Parameter	Total[a,b]
Mass	58,000 metric tons
Volume	21,000 cubic meters
Number of canisters	22,147 - 22,280[c]

a. Sources: Picha (1997, Attachment 1); Picha (1998a, Attachment 1).
b. To convert metric tons to tons, multiply by 1.1023; to convert cubic meters to cubic yards, multiply by 1.3079.
c. The number of canisters depends on the amount of surplus weapons-usable plutonium immobilized (see Section A.2.4.5.2.1).

A.2.3.5.2 *Amount and Nature of Radioactivity*

The following paragraphs present radionuclide inventory information for the individual sites. They present the best available data at varying dates; however, in most cases, the data are conservative because the inventories are for dates earlier than the date of disposal, and additional radioactive decay would occur before disposal. Any differences due to varying amounts of radioactive decay are small.

Hanford Site. Table A-25 lists the estimated radionuclide inventory for Hanford high-level radioactive glass waste, including strontium-90 and cesium-137 currently stored in capsules (Picha 1997, Table RL-1). With the exception of hydrogen-3 and carbon-14, this table makes the conservative assumption that 100 percent of a radionuclide in Hanford's 177 tanks and existing capsules is vitrified. Consistent with Hanford modeling for the Integrated Data Base (DOE 1997b, page 2-24), pretreatment and vitrification would separate hydrogen-3 and carbon-14 from the high-level radioactive waste stream such

Table A-25. Radionuclide distribution for Hanford Site high-level radioactive waste.[a,b]

Radionuclide	Total curies	Curies per canister	Radionuclide	Total curies	Curies per canister
Hydrogen-3	--[c]	--	Thorium-229	1.8	1.3×10^{-4}
Carbon-14	9.6×10^{-2}	6.6×10^{-6}	Thorium-230	--	--
Chlorine-36	--	--	Thorium-232	2.1	1.5×10^{-4}
Nickel-59	9.3×10^{2}	6.4×10^{-2}	Protactinium-231	1.6×10^{2}	1.1×10^{-2}
Nickel-63	9.2×10^{4}	6.3	Uranium-232	1.2×10^{2}	8.5×10^{-3}
Cobalt-60	1.2×10^{4}	8.5×10^{-1}	Uranium-233	4.8×10^{2}	3.3×10^{-2}
Selenium-79	7.7×10^{2}	5.3×10^{-2}	Uranium-234	3.5×10^{2}	2.4×10^{-2}
Krypton-85	--	--	Uranium-235	1.5×10^{1}	1.0×10^{-3}
Strontium-90	9.7×10^{7}	6.7×10^{3}	Uranium-236	9.6	6.6×10^{-4}
Niobium-93m	2.7×10^{3}	1.9×10^{-1}	Uranium-238	3.2×10^{2}	2.2×10^{-2}
Niobium-94	--	--	Neptunium-237	1.4×10^{2}	9.7×10^{-3}
Zirconium-93	3.6×10^{3}	2.5×10^{1}	Plutonium-238	2.8×10^{3}	1.9×10^{-1}
Technetium-99	3.3×10^{4}	2.3	Plutonium-239	3.9×10^{4}	2.7
Rhodium-101	--	--	Plutonium-240	8.9×10^{3}	6.2×10^{-1}
Rhodium-102	--	--	Plutonium-241	2.3×10^{5}	1.6×10^{1}
Ruthenium-106	1.0×10^{5}	7.2	Plutonium-242	1.2	8.0×10^{-5}
Palladium-107	--	--	Americium-241	7.0×10^{4}	4.8
Tin-126	1.2×10^{3}	8.2×10^{-2}	Americium-242m	--	--
Iodine-129	3.2×10^{1}	2.2×10^{-3}	Americium-243	9.3	6.4×10^{-4}
Cesium-134	8.9×10^{4}	6.1	Curium-242	7.7×10^{1}	5.3×10^{-3}
Cesium-135	--	--	Curium-243	1.0×10^{1}	6.9×10^{-4}
Cesium-137	1.1×10^{8}	7.7×10^{3}	Curium-244	2.4×10^{2}	1.7×10^{-2}
Samarium-151	2.8×10^{6}	1.9×10^{2}	Curium-245	--	--
Lead-210	--	--	Curium-246	--	--
Radium-226	6.3×10^{-2}	4.4×10^{-6}	Curium-247	--	--
Radium-228	7.7×10^{1}	5.3×10^{-3}	Curium-248	--	--
Actinium-227	8.8×10^{1}	6.0×10^{-3}	Californium-252	--	--

a. Sources: Picha (1997, Table RL-1); Picha (1998a, Attachment 1).
b. Decayed to January 1, 1994.
c. -- = not found in appreciable quantities.

that essentially 0.0 percent and 0.002 percent of each, respectively, would be present in the glass. A large portion of iodine-129 could also be separated, but the analysis assumed a conservative 50-percent retention (Picha 1998a, Attachment 1). Table A-25 uses the estimated number of canisters (14,500) to develop the curies-per-canister value.

Idaho National Engineering and Environmental Laboratory. Table A-26 contains a baseline radionuclide distribution for the three Idaho National Engineering and Environmental Laboratory high-level radioactive waste streams. For each waste stream, the total radionuclide inventory is provided, as is the worst-case value for curies per canister. For Idaho Nuclear Technology and Engineering Center glass, the calculated inventories are decayed to 2035. For Argonne National Laboratory-West waste matrices, the calculated inventories are decayed to 2000.

Savannah River Site. The Waste Qualification Report details the projected radionuclide distribution in the high-level radioactive waste from the Savannah River Site (Plodinec and Marra 1994, page 10). Table A-27 lists the quantities of individual radionuclides in 2015, the expected time of shipment (Pearson 1998, all). The curie-per-canister values were obtained by dividing the total radionuclide projection by the expected number of canisters (5,978).

West Valley Demonstration Project. DOE used the ORIGEN2 computer code to estimate the radionuclide inventory for the West Valley Demonstration Project, simulating each Nuclear Fuel Services

Table A-26. Radionuclide distribution for Idaho National Engineering and Environmental Laboratory high-level radioactive waste.[a,b]

	INTEC glass		ANL-W ceramic[c]		ANL-W metal[c]	
Radionuclides	Total curies for 2035	Curies per canister[d]	Total curies for 2000	Curies per canister[d]	Total curies for 2000	Curies per canister[d]
Hydrogen-3	3.6×10^{3}	4.3	--[e]	--	--	--
Carbon-14	2.8×10^{-2}	8.3×10^{-5}	--	--	4.3	4.3
Chlorine-36	--	--	--	--	--	--
Cobalt-60	3.2×10^{1}	3.6×10^{-2}	--	--	3.2×10^{3}	3.2×10^{3}
Nickel-59	--	--	--	--	1.1×10^{1}	1.1×10^{1}
Nickel-63	--	--	--	--	4.1×10^{2}	3.9×10^{2}
Selenium-79	--	--	--	--	--	--
Krypton-85	--	--	--	--	--	--
Strontium-90	7.0×10^{6}	1.2×10^{4}	7.1×10^{5}	4.7×10^{4}	--	--
Niobium-93	4.7×10^{2}	1.4	--	--	2.9×10^{1}	2.9×10^{1}
Niobium-94	5.4×10^{-3}	1.6×10^{-5}	--	--	2.7	2.7
Zirconium-93	--	--	--	--	--	--
Technetium-99	3.4×10^{3}	9.9	--	--	1.3×10^{2}	1.3×10^{2}
Rhodium-101	--	--	--	--	--	--
Rhodium-102	2.0×10^{-5}	2.2×10^{-8}	--	--	--	--
Ruthenium-106	1.0×10^{-9}	8.7×10^{-13}	--	--	2.1×10^{4}	2.1×10^{4}
Palladium-107	--	--	--	--	--	--
Tin-126	8.9×10^{1}	2.6×10^{-1}	--	--	2.8	2.1
Iodine-129	5.6	1.7×10^{-2}	3.4×10^{-1}	1.8×10^{-2}	--	--
Cesium-134	3.3×10^{-2}	3.6×10^{-5}	7.9×10^{3}	5.1×10^{2}	--	--
Cesium-135	1.6×10^{2}	2.5×10^{-1}	1.6×10^{1}	8.8×10^{-1}	--	--
Cesium-137	6.0×10^{6}	1.2×10^{4}	8.5×10^{5}	5.3×104	--	--
Samarium-151	--	--	--	--	--	--
Lead-210	--	--	--	--	--	--
Radium-226	9.7×10^{-3}	7.2×10^{-5}	3.0×10^{-5}	2.1×10^{-6}	--	--
Radium-228	--	--	--	--	--	--
Actinium-227	--	--	--	--	--	--
Thorium-229	--	--	--	--	--	--
Thorium-230	4.0×10^{-1}	2.8×10^{-3}	4.7×10^{-3}	8.9×10^{-4}	--	--
Thorium-232	9.9×10^{-8}	5.0×10^{-10}	2.3×10^{-9}	1.3×10^{-10}	--	--
Protactinium-231	--	--	--	--	--	--
Uranium-232	4.6×10^{-3}	5.2×10^{-6}	2.6×10^{-3}	1.8×10^{-4}	1.2×10^{-4}	1.2×10^{-4}
Uranium-233	1.3×10^{-3}	6.1×10^{-6}	2.0×10^{-4}	1.4×10^{-5}	5.8×10^{-5}	5.8×10^{-5}
Uranium-234	1.0×10^{2}	1.1×10^{-1}	2.8	1.9×10^{-1}	7.7×10^{-1}	7.7×10^{-1}
Uranium-235	5.9×10^{-1}	6.6×10^{-4}	8.8×10^{-2}	5.9×10^{-3}	2.5×10^{-2}	2.5×10^{-2}
Uranium-236	1.5	1.7×10^{-3}	6.3×10^{-2}	4.2×10^{-3}	1.8×10^{-2}	1.8×10^{-2}
Uranium-238	2.9×10^{-2}	3.3×10^{-5}	2.8×10^{-1}	4.9×10^{-3}	9.7×10^{-2}	8.8×10^{-2}
Neptunium-237	6.3	2.8×10^{-2}	1.3	5.8×10^{-2}	2.4×10^{-5}	2.3×10^{-5}
Plutonium-238	9.0×10^{4}	1.0×10^{2}	3.6×10^{2}	2.9×10^{1}	6.6×10^{-3}	6.6×10^{-3}
Plutonium-239	1.8×10^{3}	2.0	1.7×10^{4}	8.1×10^{2}	3.3×10^{-1}	3.3×10^{-1}
Plutonium-240	1.6×10^{3}	1.8	1.5×10^{3}	6.9×10^{1}	2.9×10^{-2}	2.9×10^{-2}
Plutonium-241	1.9×10^{4}	2.2×10^{1}	1.1×10^{4}	1.3×10^{3}	1.9×10^{-1}	1.9×10^{-1}
Plutonium-242	3.4	3.8×10^{-3}	1.2×10^{-1}	2.3×10^{-2}	2.0×10^{-6}	2.0×10^{-6}
Americium-241	1.3×10^{4}	1.4×10^{1}	1.6×10^{3}	3.4×10^{1}	3.1×10^{-2}	2.1×10^{-2}
Americium-242/242m	1.5×10^{-2}	9.4×10^{-5}	1.4×10^{1}	2.1×10^{-1}	2.7×10^{-4}	2.1×10^{-4}
Americium-243	1.4×10^{-2}	1.1×10^{-4}	2.8×10^{-1}	1.9×10^{-2}	4.8×10^{-6}	4.8×10^{-6}
Curium-242	1.2×10^{-2}	7.7×10^{-5}	1.2×10^{1}	1.8×10^{-1}	2.3×10^{-4}	1.8×10^{-4}
Curium-243	4.7×10^{-4}	3.4×10^{-6}	1.6×10^{-1}	3.1×10^{-3}	3.0×10^{-6}	2.1×10^{-6}
Curium-244	1.0×10^{-2}	7.7×10^{-5}	1.9	1.3×10^{-1}	3.1×10^{-5}	3.1×10^{-5}
Curium-245	3.7×10^{-6}	2.8×10^{-8}	6.8×10^{-5}	4.7×10^{-6}	1.1×10^{-9}	1.1×10^{-9}
Curium-246	8.7×10^{-8}	6.6×10^{-10}	4.2×10^{-7}	2.9×10^{-8}	7.1×10^{-12}	7.1×10^{-12}
Curium-247	3.1×10^{-14}	2.4×10^{-16}	2.4×10^{-13}	1.6×10^{-14}	4.0×10^{-18}	4.0×10^{-18}
Curium-248	9.4×10^{-15}	7.2×10^{-17}	2.6×10^{-14}	1.8×10^{-15}	4.4×10^{-19}	4.4×10^{-19}
Californium-252	--	--	6.5×10^{-19}	1.6×10^{-19}	--	--

a. Sources: Picha (1997, Table ID-2); Goff (1998a, all).
b. INTEC = Idaho Nuclear Technology and Engineering Center; ANL-W = Argonne National Laboratory-West.
c. Matrices based on treating all sodium-bonded fuels. Waste input streams and associated radioactivity for 2000 averaged for total number of canisters produced. Curie values based on calculated data from stored material.
d. Curie per canister values were provided as worst case rather than a homogenous mixture.
e. -- = not found in appreciable quantities.

Table A-27. Radionuclide distribution for Savannah River Site high-level radioactive waste (2015).[a]

Radionuclide	Total (curies)	Curies per canister	Radionuclide	Total (curies)	Curies per canister
Hydrogen-3	--[b]	--	Thorium-229	--	--
Carbon-14	--	--	Thorium-230	2.4×10^{-2}	4.0×10^{-6}
Chlorine-36	--	--	Thorium-232	--	--
Nickel-59	1.1×10^{2}	1.8×10^{-2}	Protactinium-231	--	--
Nickel-63	1.2×10^{4}	2.1	Uranium-232	--	--
Cobalt-60[c]	--	4.5×10^{1}	Uranium-233	--	--
Selenium-79	1.1×10^{3}	1.8×10^{-1}	Uranium-234	1.6×10^{2}	2.7×10^{-2}
Krypton-85	--	--	Uranium-235	--	--
Strontium-90	1.7×10^{8}	2.9×10^{4}	Uranium-236	--	--
Niobium-93m	1.3×10^{4}	2.2	Uranium-238	5.0×10^{1}	8.3×10^{-3}
Niobium-94	--	--	Neptunium-237	4.1×10^{2}	6.8×10^{-2}
Zirconium-93	3.0×10^{4}	5.0	Plutonium-238	3.0×10^{6}	5.0×10^{2}
Technetium-99	1.5×10^{4}	2.5	Plutonium-239	3.7×10^{4}	6.2
Rhodium-101	--	--	Plutonium-240	2.5×10^{4}	4.1
Rhodium-102	--	--	Plutonium-241	3.3×10^{6}	5.4×10^{2}
Ruthenium-106[c]	--	2.4	Plutonium-242	3.5×10^{1}	5.8×10^{-3}
Palladium-107	7.3×10^{1}	1.2×10^{-2}	Americium-241	1.6×10^{5}	2.6×10^{1}
Tin-126	2.6×10^{3}	4.3×10^{-1}	Americium-242m	--	--
Iodine-129	--	--	Americium-243	1.1×10^{3}	1.8×10^{-1}
Cesium-134[c]	--	1.2×10^{1}	Curium-242	--	--
Cesium-135	4.0×10^{2}	6.7×10^{-2}	Curium-243	--	--
Cesium-137	1.5×10^{8}	2.4×10^{4}	Curium-244	4.9×10^{5}	8.3×10^{1}
Samarium-151	3.3×10^{6}	5.5×10^{2}	Curium-245	--	--
Lead-210	--	--	Curium-246	--	--
Radium-226	--	--	Curium-247	--	--
Radium-228	--	--	Curium-248	--	--
Actinium-227	--	--	Californium-252	--	--

a. Sources: Plodinec and Marra (1994, page 10); Pearson (1998, all).
b. -- = not found in appreciable quantities.
c. Total curie content not provided for these nuclides; curie per canister values provided for 10 years after production.

irradiated fuel campaign. A detailed description of the development of these estimates is in the West Valley Demonstration Project Waste Qualification Report (WVNS 1996, WQR-1.2, Appendix 1). Table A-28 lists the estimated activity by nuclide and provides the total curies, as well as the curies per canister, based on 260 canisters.

A.2.3.5.3 *Chemical Composition*

Hanford Site. The Integrated Data Base (DOE 1997b, page 2-29) provides the best available information for the proposed representative chemical composition of future high-level radioactive waste glass from Hanford. Table A-29 combines the percentages by weight of chemical constituents obtained from the Integrated Data Base with the estimated mass to present the expected chemical composition of the glass in terms of mass per chemical compound.

Idaho National Engineering and Environmental Laboratory

Idaho Nuclear Technology and Engineering Center Glass Matrix. This waste stream is composed of three primary sources—zirconium calcine, aluminum calcine, and sodium-bearing waste.

The distribution of these sources is 55 percent, 15 percent, and 30 percent, respectively (Heiser 1998, all). Table A-30 lists the chemical composition of the total waste stream.

Table A-28. Radionuclide distribution for West Valley Demonstration Project high-level radioactive waste (2015).[a]

Radionuclide	Total curies	Curies per canister	Radionuclide	Total curies	Curies per canister
Hydrogen-3	2.0×10^{1}	7.8×10^{-2}	Thorium-229	2.3×10^{-1}	8.9×10^{-4}
Carbon-14	1.4×10^{2}	5.3×10^{-1}	Thorium-230	6.0×10^{-2}	2.3×10^{-4}
Chlorine-36	--[b]	--	Thorium-232	1.6	6.3×10^{-3}
Nickel-59	1.1×10^{2}	4.1×10^{-1}	Protactinium-231	1.5×10^{1}	5.9×10^{-2}
Nickel-63	7.1×10^{3}	2.7×10^{1}	Uranium-232	5.9	2.3×10^{-2}
Cobalt-60	2.9×10^{1}	1.1×10^{-1}	Uranium-233	9.5	3.7×10^{-2}
Selenium-79	6.0×10^{1}	2.3×10^{-1}	Uranium-234	5.0	1.9×10^{-2}
Krypton-85	--	--	Uranium-235	1.0×10^{-1}	3.9×10^{-4}
Strontium-90	3.7×10^{6}	1.4×10^{4}	Uranium-236	3.0×10^{-1}	1.1×10^{-3}
Niobium-93m	2.5×10^{2}	9.5×10^{-1}	Uranium-238	8.5×10^{-1}	3.3×10^{-3}
Niobium-94	--	--	Neptunium-237	2.4×10^{1}	9.2×10^{-2}
Zirconium-93	2.7×10^{2}	1.1	Plutonium-238	7.0×10^{3}	2.7×10^{1}
Technetium-99	1.7×10^{3}	6.5	Plutonium-239	1.7×10^{3}	6.4
Rhodium-101	--	--	Plutonium-240	1.2×10^{3}	4.7
Rhodium-102	--	--	Plutonium-241	2.5×10^{4}	9.5×10^{1}
Ruthenium-106	5.0×10^{-7}	1.9×10^{-9}	Plutonium-242	1.7	6.4×10^{-3}
Palladium-107	1.1×10^{1}	4.2×10^{-2}	Americium-241	5.3×10^{4}	2.0×10^{2}
Tin-126	1.0×10^{2}	4.0×10^{-1}	Americium-242m	2.7×10^{2}	1.0
Iodine-129	2.1×10^{-1}	8.1×10^{-4}	Americium-243	3.5×10^{2}	1.3
Cesium-134	1.2	4.4×10^{-3}	Curium-242	2.2×10^{2}	8.4×10^{-1}
Cesium-135	1.6×10^{2}	6.2×10^{-1}	Curium-243	7.3×10^{1}	2.8×10^{-1}
Cesium-137	4.1×10^{6}	1.6×10^{4}	Curium-244	2.9×10^{3}	1.1×10^{1}
Samarium-151	7.0×10^{4}	2.7×10^{2}	Curium-245	8.8×10^{-1}	3.4×10^{-3}
Lead-210	--	--	Curium-246	1.0×10^{-1}	3.9×10^{-4}
Radium-226	--	--	Curium-247	--	--
Radium-228	1.6	6.3×10^{-3}	Curium-248	--	--
Actinium-227	1.2×10^{1}	4.6×10^{-2}	Californium-252	--	--

a. Source: WVNS (1996, WQR-1.2, Appendix 1).
b. -- = not found in appreciable quantities.

Table A-29. Expected chemical composition of Hanford high-level radioactive waste glass (kilograms).[a,b]

Compound	Mass	Compound	Mass
Aluminum oxide	4,100,000	Sodium oxide	5,190,000
Boron oxide	3,090,000	Sodium sulfate	44,000
Bismuth trioxide	510,000	Nickel monoxide	480,000
Calcium oxide	370,000	Phosphorous pentaoxide	690,000
Ceric oxide	500,000	Lead monoxide	62,000
Chromic oxide	160,000	Silicon oxide	20,300,000
Ferric oxide	1,980,000	Strontium oxide	79,000
Potassium oxide	75,000	Thorium dioxide	4,400
Lanthanum oxide	48,000	Uranium oxide	2,940,000
Lithium oxide	880,000	Zirconium dioxide	1,630,000
Manganese dioxide	510,000	Other	75,000
Sodium fluoride	280,000	**Total**	**44,000,000**

a. Sources: DOE (1997b, page 2-29); Picha (1998a, Attachment 1).
b. To convert kilograms to pounds, multiply by 2.2046.

Argonne National Laboratory-West Ceramic and Metal Matrices. Electrometallurgical processing of DOE spent nuclear fuel containing thermal-bond sodium would result in two high-level radioactive waste forms for repository disposal, depending on decisions to be based on an going EIS [DOE/EIS-0306

Table A-30. Expected glass matrix chemical composition at Idaho Nuclear Technology and Engineering Center (kilograms).[a,b]

Compound or element	Mass	Compound or element	Mass
Aluminum oxide	130,000	Silicon oxide	1,020,000
Ammoniummolybdophosphate	26,000	Zirconium dioxide	18,000
Boron oxide	200,000	Arsenic	100
Calcium fluoride	140,000	Cadmium	42,000
Calcium oxide	4,100	Chromium	14,000
Ceric oxide	300	Mercury[c]	200
Ferric oxide	800	Nickel	1,400
Sodium oxide	250,000	Lead	1,800
Phosphorous pentaoxide	1,000	**Total[d]**	**1,860,000**

a. Sources: Picha (1997, Table ID-3); Heiser (1998, all).
b. Masses are rounded to the nearest 100 kilograms; to convert kilograms to pounds, multiply by 2.2046.
c. Assumes only 0.1 percent capture of original mercury in the feed materials.
d. Trace amounts of antimony, beryllium, barium, selenium, silver, and thallium were also reported.

(Notice of Intent, 64 *FR* 8553, February 22, 1999)]. The first form would be a glass-bonded ceramic composite.

It would stabilize the alkali, alkaline earth, lanthanide, halide, and transuranic materials in processed spent nuclear fuel. These elements would be present as halides after fuel treatment. For disposal, these compounds would be stabilized in a zeolite-based material (Goff 1998a, all).

The chemical formula for zeolite-4A, the typical starting material, is $Na_{12}[(AlO_2)_{12}(SiO_2)_{12}]$. In the waste form, zeolite would contain approximately 10 to 12 percent of the halide compounds by weight. The zeolite mixture typically would be combined with 25-percent glass frit by weight, placed in a stainless-steel container, and processed into a solid monolith using a hot isostatic press. The zeolite would convert to the mineral sodalite in the process (Goff 1998a, all). Table A-31 lists the composition of the waste form.

Table A-31. Expected ceramic waste matrix chemical composition at Argonne National Laboratory-West (kilograms).[a,b]

Component	Mass	Component	Mass
Zeolite-4A	92,000	Potassium iodide	10
Silicon oxide	24,000	Cesium chloride	160
Boron oxide	6,800	Barium chloride	70
Aluminum oxide	2,500	Lanthium chloride	90
Sodium oxide	2,700	Ceric chloride	140
Potassium oxide	140	Praseodymium chloride	70
Lithium-potassium chloride	13,000	Neodymium chloride	240
Sodium chloride	980	Samarium chloride	40
Rubidium chloride	20	Yttrium chloride	60
Strontium chloride	70	**Total[c]**	**144,000**

a. Source: Goff (1998a, all).
b. To convert kilograms to pounds, multiply by 2.2046.
c. Includes trace amounts of potassium bromide and europium chloride.

The halide composition would depend on the fuel processed. The final bulk composition of the ceramic waste form by weight percentages would be 25 percent glass, 63 to 65 percent zeolite-4A, and 10 to 12 percent halide salts.

Table A-32 lists the estimated composition of the second high-level radioactive waste form, which is a metal matrix waste form. The table combines percentage weight distribution with the total expected mass of the metal waste form to achieve a distributed mass by element (Goff 1998a, all).

Savannah River Site. Fowler et al. (1995, page 4) describes the chemical composition of the Defense Waste Processing Facility glass in detail. Table A-33 lists the distributed mass of the chemical constituents that comprise the current design-basis glass for the Savannah River Site. These values are based on a total mass of the glass of 11,600 metric tons (12,800 tons) (Picha 1997, Attachment 1).

West Valley Demonstration Project. The West Valley Demonstration Project will produce a single type of vitrified high-level radioactive waste. WVNS (1996, WQR-1.1, page 7) provides a target composition for all chemical constituents in the high-level radioactive waste. Table A-34 lists the expected chemical composition based on this target composition and the upper range of the projected total glass mass, 630 metric tons (694 tons).

Table A-32. Expected metal waste matrix chemical composition at Argonne National Laboratory-West (kilograms).[a]

Component	Mass
Iron	4,200
Chromium	1,500
Nickel	1,100
Manganese	180
Molybdenum	220
Silicon	90
Zirconium	1,400
NMFPs[b]	360
Others[c]	20
Total	**9,000**

a. Source: Goff (1998a, all); to convert kilograms to pounds, multiply by 2.2046.
b. NMFPs = Noble metal fission products; includes silver, niobium, palladium, rhodium, ruthenium, antimony, tin, tantalum, technetium, and cobalt in small amounts.
c. Others include trace amounts of carbon, phosphorus, and sulfur.

A.2.3.5.4 *Thermal Output*

Hanford Site. The estimated total thermal power from radioactive decay in the 14,500 reference canisters would be 1,190 kilowatts (as of January 1, 1994). This total heat load equates to an average power of 82 watts per canister. These values represent the hypothetical situation in which washed sludges from 177 tanks, cesium concentrates from the decontamination of low-level supernates, and strontium and cesium materials from capsules would be uniformly blended before vitrification. Realistically, uniform blending would not be likely. Current planning calls for merging all capsule materials with tank wastes from 2013 through 2016, which would create much hotter canisters during these years. In the extreme, the nonuniform blending of cesium concentrates and capsule materials into a relatively small volume of sludge waste could produce a few canisters with specific powers as high as 2,540 watts, which is the limit for the nominally 4.5-meter (15-foot) Hanford canisters in the Civilian Radioactive Waste Management System Baseline (Picha 1997, Attachment 1, page 2; Taylor 1997, all).

Table A-33. Expected Savannah River Site high-level radioactive waste chemical composition (kilograms).[a,b]

Glass component	Mass	Glass component	Mass
Aluminum oxide	460,000	Sodium chloride	22,000
Barium sulfate	31,000	Neodymium	13,000
Calcium oxide	110,000	Nickel monoxide	100,000
Calcium sulfate	9,300	Neptunium	100
Cadmium	140	Promethium	210
Cerium	6,800	Praseodymium	3,300
Chromic oxide	14,000	Rubidium	120
Cesium oxide	14,000	Selenium	270
Copper oxide	51,000	Silicon oxide	5,800,000
Europium	200	Samarium	2,200
Ferric oxide	1,200,000	Tin	120
Potassium oxide	450,000	Tellurium	2,200
Lanthanum	3,500	Thorium dioxide	22,000
Lithium oxide	510,000	Titanium dioxide	100,000
Magnesium oxide	160,000	Uranium oxide	250,000
Manganese oxide	230,000	Zirconium	13,000
Molybdenum	14,000	Other[c]	58,000
Sodium oxide	1,000,000		
Sodium sulfate	12,000	**Total**	**11,600,000**

a. Sources: Fowler et al. (1995, page 4); Picha (1997, Attachment 1).
b. To convert kilograms to pounds, multiply by 2.2046.
c. Includes trace amounts of silver, americium, cobalt, and antimony.

Table A-34. Expected West Valley Demonstration Project chemical composition (kilograms).[a,b]

Compound	Mass	Compound	Mass
Aluminum oxide	38,000	Nickel monoxide	1,600
Boron oxide	82,000	Phosphorous pentaoxide	7,600
Barium oxide	1,000	Rubidium oxide	500
Calcium oxide	3,000	Silicon oxide	260,000
Ceric oxide	2,000	Strontium oxide	100
Chromic oxide	900	Thorium dioxide	23,000
Ferric oxide	76,000	Titanium dioxide	4,300
Potassium oxide	32,000	Uranium oxide	3,000
Lithium oxide	24,000	Zinc oxide	100
Magnesium oxide	5,600	Zirconium dioxide	7,100
Manganese oxide	5,200	Others	3,900
Sodium oxide	51,000		
Neodymium oxide	900	**Total**	**630,000**

a. Sources: WVNS (1996, WQR-1.1, page 7); Picha (1998c, page 3).
b. To convert kilograms to pounds, multiply by 2.2046.

Idaho National Engineering and Environmental Laboratory. The Laboratory has three proposed high-level radioactive waste streams. Table A-35 lists the thermal output of these waste streams per waste canister.

Savannah River Site. The radionuclide inventories reported for the Savannah River Site high-level radioactive waste in Section A.2.3.5.2 were used to calculate projected heat generation rates for single canisters.

For the design-basis waste form, the heat generation rates 10 and 20 years after production are 465 and 302 watts per canister, respectively (Plodinec, Moore, and Marra 1993, pages 8 and 9).

Table A-35. Idaho National Engineering and Environmental Laboratory waste stream thermal output (watts).[a,b]

Output per waste canister	INTEC glass matrix	ANL-W ceramic matrix	ANL-W metal matrix
Average[c]	7.1	160	170
Worst case [d]	180	620	410

a. Source: Picha (1997, Attachment 1, page 2).
b. INTEC = Idaho Nuclear Technology and Engineering Center; ANL-W = Argonne National Laboratory-West.
c. Based on average case; 2035 used as base year for Idaho Nuclear Technology and Engineering Center glass and 2000 for ANL-W matrices.
d. Based on worst case; 2020 used as base year for Idaho Nuclear Technology and Engineering Center glass and 2000 for ANL-W matrices.

West Valley Demonstration Project. West Valley has calculated heat generation rates for a nominal West Valley canister after several different decay times (WVNS 1996, WQR-3.8, page 2). In the nominal case, the ORIGEN2-computed heat generation rate was 324 watts at the calculational base time in 1988. The heat generation rate would decrease continuously from 324 watts to about 100 watts after 50 years of additional decay.

A.2.3.5.5 *Quantity of Waste Per Canister*

Table A-36 lists the estimated mass of glass per waste canister for each high-level radioactive waste stream.

Table A-36. Mass of high-level radioactive waste glass per canister (kilograms).[a]

Waste stream[b]	Mass per canister	Source
Hanford	3,040	Picha (1997, Attachment 1, page 2)
INEEL		
INTEC	1,560	Picha (1997, Attachment 1, page 2)
ANL-W ceramic[c]	960 - 1,500	Goff (1998a, all)
ANL-W metal[c]	1,500 - 4,850	Goff (1998a, all)
Savannah River Site	2,000	Pearson (1998, all)
WVDP	2,000	Picha (1997, Attachment 1, page 2)

a. To convert kilograms to pounds, multiply by 2.2046.
b. INEEL = Idaho National Engineering and Environmental Laboratory; INTEC = Idaho Nuclear Technology and Engineering Center; ANL-W = Argonne National Laboratory-West; WVDP = West Valley Demonstration Project.
c. These values are estimates. ANL-W is evaluating waste package configurations compatible with existing storage and remote hot cell facilities. The geometries would be compatible with the Defense Waste Processing Facility high-level radioactive waste canister.

A.2.3.5.6 *High-Level Radioactive Waste Canister Parameters*

Hanford Site. Table A-37 lists preliminary physical parameters for a Hanford Tank Waste Remediation System standard canister (Picha 1997, Table RL-3).

Idaho National Engineering and Environmental Laboratory. The Idaho Nuclear Technology and Engineering Center would use stainless-steel canisters identical in design to those used at the Savannah River Site in the Defense Waste Processing Facility. A similar canister would also be used to contain the ceramic and metal waste matrices resulting from the proposed high-level radioactive waste processing at Argonne National Laboratory-West (Picha 1997, Table ID-1).

Table A-37. Parameters of proposed Tank Waste Remediation System standard canister for Hanford high-level radioactive waste disposal.[a]

Parameter	Value[b]	Comments[c]
Length	4.50 meters	1.5 meters longer than DWPF and WVDP canisters - nominal 4.5-meter length
Outer diameter	0.61 meter	Same as DWPF and WVDP canisters
Material	304 stainless steel	Same as DWPF and WVDP canisters
Wall thickness	0.95 centimeter	Same as DWPF
Canister weight	720 kilograms	
Flange opening	0.41 meters	Same as WVDP canister; large opening
Dished bottom	Yes	Same as DWPF and WVDP
Available volume	1.2 cubic meters	
Nominal percent fill	90 percent	Provides approximately same void volume as WVDP canister
Glass volume	1.1 cubic meters	

a. Source: Picha (1997, Table RL-3).
b. To convert meters to feet, multiply by 3.2808; to convert centimeters to inches, multiply by 0.3937; to convert kilograms to tons, multiply by 0.0011023; to convert cubic meters to cubic feet, multiply by 35.314.
c. DWPF = Defense Waste Processing Facility; WVDP = West Valley Demonstration Project.

Savannah River Site. The fabrication specifications of the Defense Waste Processing Facility high-level radioactive waste canisters are described in detail in Marra, Harbour, and Plodinec (1995, all). The canisters are fabricated from four basic pieces of A240 304L austenitic stainless steel—the main cylinder, the bottom head, the top head, and a nozzle. The nominal wall thickness of the canister is 0.95 centimeter (0.37 inch).

West Valley Demonstration Project. The West Valley canister is designed, fabricated, and handled in accordance with the specifications in the West Valley Demonstration Project Waste Qualification Report (WVNS 1996, WQR-2.2, all). The West Valley canisters are fabricated from four principal 304L austenitic stainless-steel components. The nominal wall thickness of the canister is 0.34 centimeter (0.13 inch).

A.2.3.5.7 *Nonstandard Packages*

Each site that would ship high-level radioactive waste to the repository has provided additional data on an estimate of nonstandard packages for possible inclusion in the candidate waste material. The mass, volume, and radioactivity of potential nonstandard packages would be dominated by failed melters from the vitrification facilities. Final disposition plans for these melters are in development and vary from site to site. The EIS used the following assumptions to estimate the potential inventory.

Hanford Site. DOE could need to ship such nonstandard high-level radioactive waste packages as failed melters and failed contaminated high-level radioactive waste processing equipment to the repository. For this EIS, the estimated volume of nonstandard packages available for shipment to the repository from the Hanford Site would be equivalent to that described below for the Savannah River Site.

Idaho National Engineering and Environmental Laboratory. DOE proposes to treat and dispose of nonstandard packages under existing regulations. However, to bound the number of failed melters the Idaho National Engineering and Environmental Laboratory could ship to the repository, this EIS uses the same ratio of failed melters to the number of canisters produced as the Savannah River Site (Palmer 1997, page 2). The Idaho National Engineering and Environmental Laboratory would produce approximately 20 percent of the number of canisters produced at the Savannah River Site, which assumes 10 failed

melters. Therefore, the Idaho National Engineering and Environmental Laboratory assumes two failed melters. The volumes and other parameters would then be twice the values listed in Table A-38 for an individual melter.

Table A-38. Parameters of nonstandard packages from Savannah River Site.[a]

Parameter	Value
Volume	10 melters based on current planning to 2021
Activity	4.5 equivalent DWPF[b] canisters for each melter
Mass	1,000 metric tons[c] for 10 melters (filled melter: 100 metric tons)
Chemical composition	Glass (see Section A.2.3.5.3) Melter – Refractory brick Aluminum Stainless steel Inconel
Quantity per disposal package	1 melter per disposal package
Thermal generation	4.5 times the heat generation of a single canister for each melter

a. Source: Pearson (1997, Attachment 1, pages 3 and 4).
b. DWPF = Defense Waste Processing Facility.
c. To convert metric tons to tons, multiply by 1.1023.

Savannah River Site. Table A-38 lists the estimated parameters of nonstandard packages for repository shipment from the Savannah River Site.

West Valley Demonstration Project. The West Valley Demonstration Project anticipates that it would send only one melter to the repository at the end of the waste solidification campaign. It would be treated as a nonstandard waste package. Table A-39 lists the estimated parameters of nonstandard packages from the West Valley Demonstration Project.

Table A-39. Parameters of nonstandard packages from West Valley Demonstration Project.[a]

Parameter	Value[b]
Volume	1 melter (24 cubic meters)
Activity	1.1 equivalent West Valley canisters
Mass	52 metric tons
Chemical composition	Melter refractories (38 metric tons) Inconel (11 metric tons) Stainless steel (1.6 metric tons) Glass (see Table A-34)
Quantity per disposal package	1 melter per package
Thermal generator	1.1 times the heat generation of a single canister (A.2.3.5.4)

a. Source: Rowland (1997, all).
b. To convert cubic meters to cubic feet, multiply by 35.314; to convert metric tons to tons, multiply by 1.1023.

A.2.4 SURPLUS WEAPONS-USABLE PLUTONIUM

A.2.4.1 Background

The President has declared approximately 50 metric tons (55 tons) of weapons-usable plutonium to be surplus to national security needs (DOE 1998a, page 1-1). This material includes the following:

- Purified plutonium in various forms (metal, oxide, etc.)
- Nuclear weapons components (pits)

- High-purity materials that DOE could process in the future to produce purified plutonium
- Plutonium residues that DOE previously saved for future recovery of purified plutonium

These materials are currently stored at the Pantex Plant, the Rocky Flats Environmental Technology Site, the Savannah River Site, the Hanford Site, the Idaho National Engineering and Environmental Laboratory (Argonne National Laboratory-West), and the Oak Ridge, Los Alamos, and Lawrence Livermore National Laboratories. DOE would draw the specific surplus weapons-usable plutonium it ultimately disposed of from the larger inventory primarily stored at these sites.

DOE could process the surplus weapons-usable plutonium as two material streams. One stream would be an immobilized plutonium ceramic form that DOE would dispose of using a can-in-canister technique with high-level radioactive waste. The second stream would be mixed uranium and plutonium oxide fuel assemblies that would be used for power production in light-water reactors and disposed of as commercial spent nuclear fuel. The Surplus Plutonium Disposition Environmental Impact Statement (DOE 1998a, page 1-1) evaluates the quantity of plutonium processed in each stream. This EIS assumes that approximately 18 metric tons (20 tons) of surplus weapons-usable plutonium would be immobilized and approximately 32 metric tons (35 tons) would be made into mixed-oxide commercial nuclear fuel. The actual split could include the immobilization of between 18 and 50 metric tons (55 tons).

A.2.4.2 Sources

DOE would produce the immobilized plutonium and/or mixed-oxide fuel at sites determined in a Record of Decision for the Surplus Plutonium Disposition Environmental Impact Statement (DOE 1998a, page 1-9). The Department has selected for further environmental review six alternative commercial light-water reactors in which it proposes to irradiate the mixed-oxide fuel: both units at Catawba in York, South Carolina; both units at McGuire in Huntersville, North Carolina; and both units at North Anna Power Station in Mineral Springs, Virginia (DOE 1999, all).

A.2.4.3 Present Storage and Generation Status

DOE would begin production of the immobilized plutonium in 2006 with an estimated completion by 2016. The immobilization of 18 metric tons (20 tons) of plutonium would produce an estimated 77 additional canisters of high-level radioactive waste, which the production location would store until shipment to the repository. The immobilization of 50 metric tons (55 tons) of plutonium would produce an estimated 210 additional canisters of high-level radioactive waste. This EIS assumes that the production location would be the Savannah River Site and, therefore, used the physical dimensions of the Defense Waste Processing Facility canisters to calculate these values (DOE 1998a, pages 2-26 and 2-27).

Commercial light-water reactors would use mixed-oxide fuel assemblies for power production starting as early as 2007. This fuel would replace the low-enriched uranium fuel that normally would be in the reactors. After the fuel assemblies were discharged from the reactors as spent mixed-oxide fuel, the reactor sites would store them until shipment to the repository. Mixed-oxide fuel use would produce an insignificant number of additional spent nuclear fuel assemblies (less than 0.1 percent) (DOE 1998a, page 4-378).

A.2.4.4 Final Waste Form

The final waste form would be immobilized plutonium or spent mixed-oxide fuel. Section A.2.4.5 discusses the characteristics of these materials. The spent mixed-oxide fuel discussed here has different characteristics than the mixed-oxide fuel included in the National Spent Fuel Program (LMIT 1997, all) and described in Section A.2.2.

A.2.4.5 Material Characteristics

A.2.4.5.1 *Mixed-Oxide Fuel*

A.2.4.5.1.1 Mass and Volume. The EIS on surplus weapons-usable plutonium disposition (DOE 1998a, page 1-9) evaluates the disposal of approximately 32 metric tons (35 tons) of plutonium as mixed-oxide fuel. The amount of plutonium and uranium measured in metric tons of heavy metal going to a repository would depend on the average percentage of plutonium in the fuel. The percentage of plutonium would be influenced by the fuel design. DOE has chosen pressurized-water reactors for the proposed irradiation of these assemblies. For pressurized-water reactors, the expected average plutonium percentages would be approximately 4.6 percent; however, they could range between 3.5 and 6 percent (Stevenson 1997, pages 5 and 6). Table A-40 lists estimates and ranges for the total metric tons of heavy metal (uranium and plutonium) that would result from disposing of 32 metric tons (35 tons) of plutonium in mixed-oxide fuel. The table also lists a corresponding estimate for the number of assemblies required, based on using the typical assemblies described in Section A.2.1.4. The ranges of metric tons of heavy metal account for the proposed range in potential plutonium percentage.

Table A-40. Estimated spent nuclear fuel quantities for disposition of 32 metric tons of plutonium in mixed-oxide fuel.[a,b]

Reactor and fuel type	Plutonium percentage	Best estimate (MTHM)	Assemblies required	Range (MTHM)
Pressurized-water reactor	4.56	700	1,500	500-900

a. Source: Stevenson (1997, pages 5 and 6).
b. MTHM = metric tons of heavy metal; to convert metric tons to tons, multiply by 1.1023.

DOE assumed that each spent mixed-oxide assembly irradiated and disposed of would replace an energy-equivalent, low-enriched uranium assembly originally intended for the repository. The mixed-oxide assemblies would be part of the 63,000 metric tons (69,000 tons) that comprise the commercial spent nuclear fuel disposal amount in the Proposed Action (Person 1998, all). DOE also assumes that the average burnup levels for the pressurized-water reactor would be the same as that for the energy-equivalent, low-enriched uranium fuel. Table A-41 lists the assumed burnup levels and the amount of heavy metal in an assembly.

Table A-41. Assumed design parameters for typical mixed-oxide assembly.[a]

Parameter	Pressurized-water reactor
Mixed-oxide and low-enriched uranium burnup (MWd/MTHM)[b]	45,000
Mixed-oxide assembly mass (kilograms[c] of heavy metal)	450
Mixed-oxide assembly percentage of plutonium	4.56

a. Source: Stevenson (1997, page 7).
b. MWd/MTHM = megawatt days per metric ton of heavy metal; to convert metric tons to tons, multiply by 1.1023.
c. To convert kilograms to pounds, multiply by 2.2046.

The analysis assumed that the mixed-oxide spent nuclear fuel would replace the low-enriched uranium fuel. Because of the similarities in the two fuel types, impacts to the repository would be small. Nuclear criticality, radionuclide release rates, and heat generation comparisons are evaluated in Stevenson (1997, pages 35 to 37).

A.2.4.5.1.2 Amount and Nature of Radioactivity. Tables A-42 and A-43 list isotopic composition data for spent mixed-oxide fuel assemblies. The tables reflect SCALE data files from an Oak Ridge National Laboratory report used with computer simulation to project the characteristics of spent mixed-oxide fuel in pressurized-water reactors (Ryman, Hermann, and Murphy 1998, Volume 3, Appendix B). The tables summarize data for two different potential fuel assemblies: a typical pressurized-water reactor,

Table A-42. Radionuclide activity for typical pressurized-water reactor spent mixed-oxide assembly.[a]

Isotope	Curies per assembly	Isotope	Curies per assembly
Hydrogen-3	2.0×10^{2}	Samarium-151	5.3×10^{2}
Carbon-14	3.4×10^{-1}	Uranium-234	4.9×10^{-2}
Cobalt-60	1.7×10^{3}	Uranium-235	1.0×10^{-3}
Nickel-59	1.1	Uranium-236	6.4×10^{-3}
Nickel-63	1.4×10^{2}	Uranium-238	1.4×10^{-1}
Krypton-85	1.9×10^{3}	Plutonium-238	1.2×10^{3}
Strontium-90	1.7×10^{4}	Plutonium-239	6.6×10^{2}
Zirconium-93	6.5×10^{-2}	Plutonium-240	8.6×10^{2}
Niobium-93m	2.8×10^{1}	Plutonium-241	2.0×10^{5}
Niobium-94	6.8×10^{-1}	Americium-241	2.2×10^{3}
Technetium-99	6.3	Americium-242/242m	3.4×10^{1}
Ruthenium-106	1.6×10^{4}	Americium-243	2.4×10^{1}
Iodine-129	2.1×10^{-2}	Curium-242	6.0×10^{1}
Cesium-134	1.4×10^{4}	Curium-243	3.2×10^{1}
Cesium-137	4.7×10^{4}	Curium-244	2.6×10^{3}

a. Source: Ryman, Hermann, and Murphy (1998, Volume 3, Appendix B).

Table A-43. Radionuclide activity for high-burnup pressurized-water reactor spent mixed-oxide assembly.[a]

Isotope	Curies per assembly	Isotope	Curies per assembly
Hydrogen-3	2.9×10^{2}	Uranium-234	6.8×10^{-2}
Carbon-14	5.4×10^{-1}	Uranium-235	6.7×10^{-4}
Cobalt-60	2.4×10^{3}	Uranium-236	7.7×10^{-3}
Nickel-59	1.7	Uranium-238	1.5×10^{-1}
Nickel-63	2.3×10^{2}	Plutonium-238	2.7×10^{3}
Krypton-85	2.6×10^{3}	Plutonium-239	4.6×10^{2}
Strontium-90	2.4×10^{4}	Plutonium-240	8.8×10^{2}
Niobium-93m	3.9×10^{1}	Plutonium-241	2.2×10^{5}
Niobium-94	9.8×10^{-1}	Americium-241	2.5×10^{3}
Technetium-99	9.0	Americium-242/242m	4.9×10^{1}
Ruthenium-106	1.8×10^{4}	Americium-243	5.6×10^{1}
Iodine-129	3.0×10^{-2}	Curium-242	1.0×10^{2}
Cesium-134	2.5×10^{4}	Curium-243	8.5×10^{1}
Cesium-137	7.0×10^{4}	Curium-244	8.9×10^{3}
Samarium-151	5.4×10^{2}		

a. Sources: Ryman, Hermann, and Murphy (1998, Volume 3, Appendix B).

and a high-burnup pressurized-water reactor. A high burnup pressurized-water assembly would be irradiated for three cycles in comparison to the two cycles for the typical assemblies. For each of these assemblies, the tables provide radioactivity data for the common set of nuclides used in this EIS for the assumed 5-year minimum cooling time.

A.2.4.5.1.3 Chemical Composition. Tables A-44 and A-45 list the elemental distributions for the typical and high-burnup pressurized-water reactor spent mixed-oxide fuel assemblies.

A.2.4.5.1.4 Thermal Output. Table A-46 lists the decay heat from the representative mixed-oxide spent fuel assemblies at a range of times after discharge.

A.2.4.5.1.5 Physical Parameters. Because the mixed-oxide fuel would replace low-enriched uranium fuel in existing reactors, Section A.2.1.5.5 describes the physical parameters, with the exception of uranium and plutonium content, which are listed in Table A-41.

Table A-44. Elemental distribution of typical burn-up pressurized-water reactor spent mixed-oxide assembly.[a]

Element	Grams per assembly[b]	Percent[c]	Element	Grams per assembly	Percent
Americium	770	0.12	Palladium	1,200	0.19
Barium	750	0.12	Phosphorus	140	0.02
Carbon	67	0.01	Plutonium	17,000	2.59
Cerium	1,100	0.16	Praseodymium	500	0.08
Cesium	1,500	0.23	Rhodium	360	0.05
Chromium	2,300	0.36	Rubidium	91	0.01
Europium	90	0.01	Ruthenium	1,300	0.20
Iodine	150	0.02	Samarium	440	0.07
Iron	4,600	0.71	Silicon	66	0.01
Krypton	100	0.02	Strontium	210	0.03
Lanthanum	540	0.08	Technetium	370	0.06
Manganese	110	0.02	Tellurium	260	0.04
Molybdenum	1,700	0.27	Tin	1900	0.28
Neodymium	1,700	0.26	Uranium	428,000	65.92
Neptunium	72	0.01	Xenon	2500	0.38
Nickel	4,400	0.68	Yttrium	110	0.02
Niobium	330	0.05	Zirconium	111,000	17.10
Oxygen	62,000	9.56	**Totals**	**648,000**	**99.73**

a. Source: Murphy (1998, all).
b. To convert grams to ounces, multiply by 0.035274.
c. Table includes only elements that constitute at least 0.01 percent of the total; therefore, total is slightly less than 100 percent.

Table A-45. Elemental distribution of high burn-up pressurized-water reactor spent mixed-oxide assembly.[a]

Element	Grams per assembly[b]	Percent[c]	Element	Grams per assembly	Percent
Americium	1,000	0.16	Palladium	2,000	0.30
Barium	1,200	0.18	Phosphorus	140	0.02
Carbon	70	0.01	Plutonium	14,000	2.22
Cerium	1,600	0.24	Praseodymium	750	0.11
Cesium	2,100	0.33	Rhodium	460	0.07
Chromium	2,300	0.36	Rubidium	140	0.02
Europium	140	0.02	Ruthenium	2,000	0.31
Iodine	220	0.03	Samarium	630	0.10
Iron	4,600	0.71	Silicon	66	0.01
Krypton	150	0.02	Strontium	300	0.05
Lanthanum	810	0.12	Technetium	520	0.08
Manganese	100	0.02	Tellurium	390	0.06
Molybdenum	2,500	0.39	Tin	1,900	0.29
Neodymium	2,500	0.39	Uranium	421,000	64.84
Neptunium	93	0.01	Xenon	3,700	0.57
Nickel	4,400	0.68	Yttrium	170	0.03
Niobium	330	0.05	Zirconium	111,000	17.10
Oxygen	62,000	9.56	**Totals**	**646,000**	**99.46**

a. Source: Murphy (1998, all).
b. To convert grams to ounces, multiply by 0.035274.
c. Table includes only elements that constitute at least 0.01 percent of the total; therefore, total is slightly less than 100 percent.

Table A-46. Mixed-oxide spent nuclear fuel thermal profile (watts per assembly).[a]

Years	Typical PWR[b]	High-burnup PWR
1	6,100	8,000
5	1,000	1,600
10	670	1,100
15	610	970
30	540	780
100	370	430
300	240	260
1,000	110	110
3,000	42	38
10,000	25	22
30,000	10	7.9
100,000	1.5	1.3
250,000	0.5	0.6

a. Source: Ryman, Hermann, and Murphy (1998, Volume 3, Appendix B).
b. PWR = pressurized-water reactor.

A.2.4.5.2 *Immobilized Plutonium*

At present, approximately 50 metric tons (55 tons) of weapons-usable plutonium have been declared to be surplus to national needs. DOE has not yet determined the total quantity of plutonium for immobilization. The Department assumes that approximately 32 metric tons (35 tons) is "clean" metal suitable for use in mixed-oxide fuel, and that it could dispose of this material by burning it in reactors (DOE 1998a, page 1-1). The remaining surplus plutonium would require considerable additional chemical processing to make it suitable for reactor use. This EIS evaluates two cases, one in which DOE immobilizes only the "impure" materials (base case) and a second in which it immobilizes the entire 50-metric-ton surplus inventory. The base case is evaluated for the Proposed Action because it is DOE's preferred alternative (DOE 1998a, page 1-1). The EIS evaluates the second case for potential cumulative impacts (Modules 1 and 2) because it would conservatively predict the largest number of required high-level radioactive waste canisters.

A.2.4.5.2.1 Mass and Volume. In DOE's preferred disposition alternative, immobilized plutonium would arrive at the repository in canisters of vitrified high-level radioactive waste that would be externally identical to standard canisters from the Defense Waste Processing Facility at the Savannah River Site. Smaller cans containing immobilized plutonium in ceramic disks would be embedded in each canister of high-level radioactive waste glass. This is the *can-in-canister* concept. Because the design of the can-in-canister is not final, DOE has not determined final waste loadings per canister, volume displaced by the cans, or other specifications. The current baseline concept calls for cylindrical cans that are 53 centimeters (21 inches) high with a 7.6-centimeter (3-inch) diameter. The gross volume of each can would be 2.4 liters (150 cubic inches). DOE estimates that each canister would contain 28 cans, but has not yet finalized the actual number. One of the limitations on the number of cans is determined by the ability to ensure that the high-level radioactive waste glass would fill completely around the cans; increasing the volume that the cans would occupy in a canister could increase the difficulty of achieving this. Final confirmation of the design will be confirmed by actual test pours at scale (Stevenson 1997, page 41).

Marra, Harbour, and Plodinec (1995, page 2) describes the volume of a high-level radioactive waste canister. Each canister has a design capacity of 2,000 kilograms (4,400 pounds) of high-level radioactive waste glass. A nominal glass density of 2.7 grams per cubic centimeter (0.10 pound per cubic inch)

yields a design glass volume of 620 liters (22 cubic feet). The 28 cans containing plutonium would displace 68 liters (2.4 cubic feet), or about 11 percent of the available volume. The rack holding the cans would displace about an additional 1 percent of the available volume, yielding a total displacement of about 12 percent.

Each plutonium can would contain 20 cylindrical pellets, 6.7 centimeters (2.6 inches) in diameter and 2.5 centimeters (1 inch) in height. The pellets would have an average density of 5.5 grams per cubic centimeter (0.20 pound per cubic inch) and would contain 10.5 percent of plutonium by weight. Each can, therefore, would contain about 1 kilogram (2.2 pounds) of plutonium, yielding a total of about 28 kilograms (62 pounds) per canister (1 kilogram of plutonium per can multiplied by 28 cans per canister).

Table A-47 lists the number of high-level radioactive waste canisters required to dispose of immobilized surplus plutonium using the loading and volumetric assumptions given above for both the base and 50-metric-ton (55-ton) cases. It also lists the number of additional canisters DOE would have to produce (in addition to those the high-level radioactive waste producer would already have produced) due to the displacement of high-level radioactive waste glass by the plutonium-containing canisters. The total number of required canisters would be a function of both the number of cans in each canister and the plutonium loading of the immobilization form. The number of additional canisters would depend only on the plutonium loading of the immobilization form.

Table A-47. Number of canisters required for immobilized plutonium disposition.[a,b]

Canisters	Base case	50-metric-ton case
Containing plutonium	635	1,744
In excess of those required for DWPF[c] (12% of total canisters)	77	210
Additional[d]	1.3%	3.5%

a. Source: DOE (1998a, pages 2-26 and 2-27).
b. Assumes 28 kilograms (62 pounds) of plutonium per canister and displacement of 12 percent of the high-level radioactive waste glass by plutonium cans and rack.
c. DWPF = Defense Waste Processing Facility.
d. As percentage of total planned DWPF canisters (about 6,000).

A.2.4.5.2.2 Amount and Nature of Radioactivity. Assuming the current 10.5-percent plutonium loading in the ceramic (Stevenson 1997, page 49), the expected isotopic composition of the various materials in the feedstream for ceramic production, and the nominal quantity of ceramic in each canister, Stevenson (1997, page 49) calculated the activity of the immobilized material in each high-level radioactive waste canister. The figures do not include the radioactivity of the vitrified high-level radioactive waste that would surround the cans of immobilized plutonium. Calculation of the total radioactivity of a canister requires the subtraction of approximately 12 percent from the radioactivity of a full high-level radioactive waste canister to account for the displacement of the immobilized plutonium and its rack. Those reduced numbers, added to the appropriate figures in Table A-48, produce the total activity of a plutonium-containing high-level radioactive waste canister.

Values for the base case and the 50-metric-ton case are different because the plutonium in the base case contains more transuranic radionuclides, other than plutonium-239, than does the remainder of the plutonium [32 metric tons (35 tons)]. Thus, the "other" transuranic radionuclides are diluted in the 50-metric-ton case. From a thermal output and radiological impact standpoint, the base case is a more severe condition and, therefore, DOE has used it for the Proposed Action analysis.

Section A.2.3.5.2 contains information on the radioactivity contained in a standard Defense Waste Processing Facility high-level radioactive waste canister.

Table A-48. Average total radioactivity of immobilized plutonium ceramic in a single canister in 2010 (curies).[a,b]

Nuclide	Base case	50-metric-ton case
Plutonium-238	120	60
Plutonium-239	1,600	1,700
Plutonium-240	550	430
Plutonium-241	4,700	2,800
Plutonium-242	0.098	0.046
Americium-241	720	430
Uranium-234	< 0.000015[c]	< 0.000005
Uranium-235	0.0024	< 0.0011
Uranium-238	0.019	0.019
Thorium-232	< 0.00003	< 0.00003
Totals	**7,700**	**5,400**

a. Source: Stevenson (1997, page 49).
b. Assumes 10.5 percent of plutonium by weight in ceramic form, 1:2 molar ratio of plutonium to uranium, and 28 kilograms (62 pounds) of plutonium per canister. These values account only for the radioactivity in the immobilized form; they do not include that in the surrounding high-level radioactive waste glass.
c. < = less than.

A.2.4.5.2.3 Chemical Composition. The current design for a ceramic immobilization form is a multiphase titanate ceramic, with a target bulk composition listed in Table A-49. The neutron absorbers, hafnium and gadolinium, are each present at a 1-to-1 atomic ratio to plutonium, and the atomic ratio of uranium to plutonium is approximately 2-to-1. For the base case, the presence of impurities in some categories of surplus weapons-usable plutonium would result in the presence of a few weight percent of other nonradioactive oxides in some of the actual ceramic; Table A-49 does not list these impurities (Stevenson 1997, page 51).

Table A-49. Chemical composition of baseline ceramic immobilization form.[a]

Oxide	Approximate percent by weight
Titanium oxide	36
Hafnium oxide	10
Calcium oxide	10
Gadolinium oxide	8
Plutonium oxide	12
Uranium oxide	24

a. Source: Stevenson (1997, page 51).

The ceramic phase assemblage is mostly Hf-pyrochlore [$(CaGd)(Gd,Pu,U,Hf)Ti_2O_7$], with subsidiary Hf-zirconolite [$(CaGd)(Gd,Pu,U,Hf)Ti_2O_7$)], and minor amounts of brannerite [$(U,Pu,Gd)Ti_2O_6$] and rutile [$(Ti,Hf)O_2$]. Pyrochlore and zirconolite differ in their crystalline structures. The presence of silicon as an impurity in the plutonium could lead to the formation of a minor amount of a silicate glass phase in the ceramic. This phase could contain a trace amount of the immobilized plutonium. Some residual plutonium oxide (less than 0.5 percent of the total quantity of plutonium) could also be present. The residual plutonium oxide contains uranium with smaller amounts of gadolinium and hafnium as a result of partial reaction with the other constituents of the ceramic (Stevenson 1997, page 51). Section A.2.3.5.3 describes the chemical composition of the high-level radioactive waste glass surrounding the plutonium-containing cans.

A.2.4.5.2.4 Thermal Output. Stevenson (1997, page 49) has presented the heat generation of the immobilized ceramic. These figures represent only the heat from the ceramic; they do not account for the heat from the surrounding high-level radioactive waste glass. The total heat from a Defense Waste Processing Facility canister containing high-level radioactive waste and immobilized plutonium would be the value listed in Table A-50 combined with 88 percent of the value listed in Section A.2.3.5.4 for the heat from a Defense Waste Processing Facility canister.

Table A-50. Thermal generation from immobilized plutonium ceramic in a single canister in 2010 (watts per canister).[a]

Case	Thermal production
Base case	8.6
50-metric-ton[b] case	7.0

a. Source: Stevenson (1997, page 49).
b. To convert metric tons to tons, multiply by 1.1023.

A.2.4.5.2.5 Quantity of Material Per Canister. As discussed in Section A.2.4.5.2.1, DOE has yet to determine the actual configuration of the can-in-canister disposal package. Although the final configuration could use either the Savannah River Site or Hanford canisters, this EIS assumes the use of the Savannah River Site canister. The current baseline concept (described above) would result in a per-canister loading of 28 kilograms (62 pounds) of plutonium. Table A-48 lists the radioactivities of these materials. Section A.2.3.5.5 discusses the quantity of high-level radioactive waste associated with each Defense Waste Processing Facility canister. The quantity of high-level radioactive waste in each plutonium-containing canister would be less than the nominal content of a standard Defense Waste Processing Facility canister because the displacement of the plutonium cans and the support rack would amount to an estimated 12 percent of the net canister volume.

The canisters would differ internally from normal Defense Waste Processing Facility canisters due to the presence of the stainless-steel cans of immobilized plutonium and a stainless-steel rack holding the cans in place during pouring of molten high-level radioactive waste glass into the canister.

A.2.5 COMMERCIAL GREATER-THAN-CLASS-C LOW-LEVEL WASTE

A.2.5.1 Background

Title 10 of the Code of Federal Regulations, Part 61 (10 CFR Part 61), establishes disposal requirements for three classes of waste—A, B, and C—suitable for near-surface disposal. Class C has the highest level of radioactivity and therefore the most rigorous disposal specifications. Wastes with concentrations above Class C limits (listed in 10 CFR 61.55 Tables 1 and 2 for long and short half-life radionuclides, respectively) are called Greater-Than-Class-C low-level waste, and are not generally suitable for near-surface disposal (DOE 1994, all).

Commercial nuclear powerplants, research reactors, radioisotope manufacturers, and other manufacturing and research institutions generate waste that exceeds the Nuclear Regulatory Commission Class C shallow-land-burial disposal limits. Public Law 99-240 assigns the Federal Government, specifically DOE, the responsibility for disposing of this Greater-Than-Class-C waste. DOE could use a number of techniques for the disposal of these wastes, including engineered near-surface disposal, deep borehole disposal, intermediate-depth burial, and disposal in a deep geologic repository (DOE 1994, all).

The activities of nuclear electric utilities and other radioactive waste generators to date have produced relatively small quantities of Greater-Than-Class-C waste. As the utilities take their reactors out of service and decommission them, they could generate more waste of this type (DOE 1994, all).

Greater-Than-Class-C waste could include the following materials:

- Nuclear powerplant operating wastes
- Nuclear powerplant decommissioning wastes
- Sealed radioisotope sources that exceed Class C limits for waste classification
- DOE-held Greater-Than-Class-C waste (addressed in Section A.2.6)
- Greater-Than-Class-C waste from other generators

This section describes the quantities and characteristics of these waste types.

A.2.5.2 Sources

Sources or categories of Greater-Than-Class-C waste include:

- DOE facilities (addressed in Section A.2.6)
- Nuclear utilities
- Sealed sources
- Other generators

Nuclear utility waste includes activated metals and process wastes from commercial nuclear powerplants. Sealed sources are radioactive materials in small metallic capsules used in measurement and calibration devices. Other generator wastes consist of sludge, activated metals, and other wastes from radionuclide manufacturers, commercial research, sealed-source manufacturers, and similar operations. The decommissioning of light-water reactors probably will generate additional Greater-Than-Class-C waste. Some internal reactor components will exceed Class C disposal limits.

A.2.5.3 Present Status

Nuclear utilities store their Greater-Than-Class-C waste at the generator site, where it will remain until a disposal option becomes available.

Sealed sources are held by a Nuclear Regulatory Commission or Agreement State licensee. Current DOE sealed-source management plans call for the licensees to store their sealed-source wastes until a disposal option becomes available. If storage by a licensee became physically or financially impossible and a threat to public health and safety, the Nuclear Regulatory Commission would determine if the source was a candidate for DOE storage. At that time, the Commission could request that DOE accept the source for storage, reuse, or recycling. The inventory projections do not include such a transfer of material.

In 1993, there were 13 identified “other generators” of Greater-Than-Class-C waste (DOE 1994, Appendix D), which were categorized into seven business types:

- Carbon-14 user
- Industrial research and development
- Irradiation laboratory
- Fuel fabricator
- University reactor
- Sealed-source manufacturer
- Nonmedical academic institution

These generators store their wastes at their sites and will continue to do so until a disposal site becomes operational.

A.2.5.4 Final Waste Form

The final disposition method for Greater-Than-Class-C waste is not known. If DOE was to place such waste in a repository, it is assumed that it would be placed in a disposal package before shipment. The EIS assumes the use of a package similar to the naval dual-purpose canister, which is described in Section A.2.2.5.6, for all shipments by rail and a package similar to the high-level radioactive waste canisters for all shipments by truck.

A.2.5.5 Waste Characteristics

Table A-51 lists existing and projected volumes for the three Greater-Than-Class-C waste generator sources. DOE conservatively projects the volume of nuclear utility wastes to 2055 because that date would include the majority of this waste from the decontamination and decommissioning of commercial nuclear reactors. The projected volumes conservatively reflect the highest potential volume and activity based on inventories, surveys, and industry production rates. DOE projects the other two generator sources (sealed sources and other generators) to 2035 (DOE 1994, all).

Table A-51. Greater-Than-Class-C waste volume by generator source (cubic meters).[a,b]

Source	1993 volume	Projected volume
Nuclear electric utility	26	1,300
Sealed sources	39	240
Other generators	74	470
Totals	**139**	**2,010**

a. Source: DOE (1994, all).
b. To convert cubic meters to cubic feet, multiply by 35.314.

The data concerning the volumes and projections are from Greater-Than-Class-C Waste Characterization: Estimated Volumes, Radionuclide Activities, and Other Characteristics (DOE 1994), Appendix A-1, which provides detailed radioactivity reports for such waste currently stored at nuclear utilities. Table A-52 summarizes the radioactivity data for the primary radionuclides in the waste, projected to 2055.

Table A-52. Commercial light-water reactor Greater-Than-Class-C waste radioactivity (curies) by nuclide (projected to 2055).[a]

Nuclide	Radioactivity
Carbon-14	6.8×10^{4}
Cobalt-60	3.3×10^{7}
Iron-55	1.8×10^{7}
Hydrogen-3	1.2×10^{4}
Manganese-54	3.2×10^{4}
Niobium-94	9.8×10^{2}
Nickel-59	2.5×10^{5}
Nickel-63	3.7×10^{7}
Transuranics	2.0×10^{3}
Total	$\mathbf{8.8\times10^{7}}$

a. Source: DOE (1994, Appendix A-1).

Appendix B of DOE (1994) provides detailed radioactivity reports for the sealed sources, which could be candidate wastes for the repository. Table A-53 summarizes the radioactivity data for the radionuclides in these sources, projected to 2035.

Table A-53. Sealed-source Greater-Than-Class-C waste radioactivity (curies) by nuclide (projected to 2035).[a]

Nuclide	Radioactivity
Americium-241	8.0×10^{4}
Curium-244	1.6×10^{2}
Cesium-137	4.0×10^{7}
Plutonium-238	1.6×10^{4}
Plutonium-239	1.1×10^{5}
Plutonium-241	2.8×10^{1}
Technetium-99	5.8×10^{3}
Uranium-238	5.7×10^{1}
Total	**4.2×10^{7}**

a. Source: DOE (1994, Appendix B).

DOE (1994, Section 5) also identifies the 13 other generators and the current and projected volumes and total radioactivity of Greater-Than-Class-C waste held by each. It does not provide specific radionuclide activity by nuclide. DOE used the data to derive a distribution, by user business type, of the specific nuclides that comprise the total radioactivity. Table A-54 lists this distributed radioactivity for other generators.

Table A-54. Other generator Greater-Than-Class-C waste radioactivity (in curies) by nuclide (projected to 2035).[a]

Nuclide	Radioactivity
Carbon-14	7.7×10^{3}
Transuranic	2.2×10^{3}
Cobalt-60	1.5×10^{2}
Nickel-63	1.5×10^{2}
Americium-241	2.4×10^{3}
Cesium-137	6.6×10^{1}
Technetium-99	5.1×10^{-2}
Total[b]	**1.3×10^{4}**

a. Source: Derived from DOE (1994, Appendix D).
b. Total differs from sum of values due to rounding.

A detailed chemical composition by weight percentage for current Greater-Than-Class-C waste is not available. However, Table A-55 lists the typical composition of such wastes by generator.

Table A-55. Typical chemical composition of Greater-Than-Class-C wastes.[a]

Source	Typical composition
Nuclear electric utility	Stainless steel-304, and zirconium alloys
Sealed sources	Stainless steel-304 (source material has very small mass contribution)
Other generators	Various materials

a. Source: DOE (1994, all).

The heat generation rates or thermal profiles for this waste type are not included in the source documentation. However, the contribution to the total thermal load at the repository from the Greater-Than-Class-C radioactive waste would be very small in comparison to commercial spent nuclear fuel or high-level radioactive waste.

A.2.6 SPECIAL-PERFORMANCE-ASSESSMENT-REQUIRED LOW-LEVEL WASTE

A.2.6.1 Background

DOE production reactors, research reactors, reprocessing facilities, and research and development activities generate wastes that exceed the Nuclear Regulatory Commission Class C shallow-land-burial disposal limits. The Department is responsible for the safe disposal of such waste, and could use a number of techniques such as engineered near-surface disposal, deep borehole disposal, intermediate-depth burial, or disposal in a deep geologic repository. These wastes have been designated as Special-Performance-Assessment Required wastes.

DOE Special-Performance-Assessment-Required waste could include the following materials:

- Production reactor operating wastes
- Production and research reactor decommissioning wastes
- Non-fuel-bearing components of naval reactors
- Sealed radioisotope sources that exceed Class C limits for waste classification
- DOE isotope production-related wastes
- Research reactor fuel assembly hardware

A.2.6.2 Sources

DOE has identified Special-Performance-Assessment-Required waste inventories at several locations. Table A-56 lists the generators and amounts of these wastes. These amounts include current and projected inventory. The Department will generate additional waste as it decommissions its nuclear facilities.

Table A-56. Estimated Special-Performance-Assessment-Required low-level waste volume and mass by generator source.[a]

Source[b]	Volume (cubic meters)[c]	Mass (kilograms)[d]
Hanford	20	360,000
INEEL[e]	20	280,000
ORNL	2,900	4,700,000
WVDP	550	5,200,000
ANL-E	1	230
Naval Reactors Facility	500	2,500,000
Totals	**4,000**	**13,040,230**

a. Source: Picha (1998b, all).
b. INEEL = Idaho National Engineering and Environmental Laboratory (including Argonne National Laboratory-West); ORNL = Oak Ridge National Laboratory; WVDP = West Valley Demonstration Project; ANL-E = Argonne National Laboratory-East.
c. To convert cubic meters to cubic yards, multiply by 1.3079.
d. To convert kilograms to pounds, multiply by 2.2046.
e. Includes Argonne National Laboratory-West.

A.2.6.3 Present Status

DOE stores its Special-Performance-Assessment-Required waste at the generator sites listed in Table A-56. Tables A-57 through A-60 list the waste inventories at the individual sites. For radionuclides, these tables include only the reported isotopes with inventories greater than 1×10^{-5} curies. Table A-61 lists the chemical composition of this material at each site.

Table A-57. Hanford Special-Performance-Assessment-Required low-level waste radioactivity by nuclide (curies).[a]

Nuclide	Radioactivity
Cesium-137	6.0×10^{4}
Strontium-90	6.0×10^{4}

a. Source: Picha (1998b, all).

Table A-58. Idaho National Engineering and Environmental Laboratory (including Argonne National Laboratory-West) Special-Performance-Assessment-Required low-level waste radioactivity by nuclide (curies).[a]

Nuclide	Radioactivity
Hydrogen-3	5.9×10^{6}
Carbon-14	8.3×10^{2}
Cobalt-60	1.1×10^{6}
Nickel-59	9.0×10^{1}
Nickel-63	1.3×10^{4}
Strontium-90	7.4×10^{3}
Niobium-94	1.4×10^{2}
Technetium-99	3.3
Cesium-137	3.1×10^{1}
Radium-226	3.0×10^{1}
Plutonium-239	2.0×10^{1}
Americium-241	2.4×10^{2}

a. Source: Picha (1998b, all).

Table A-59. Oak Ridge National Laboratory Special-Performance-Assessment-Required low-level waste radioactivity by nuclide (curies).[a]

Nuclide	Radioactivity
Hydrogen-3	1.9×10^{6}
Carbon-14	1.0×10^{1}
Cobalt-60	1.9×10^{6}
Nickel-59	7.6×10^{3}
Nickel-63	7.5×10^{5}
Strontium-90	8.3×10^{7}
Niobium-94	1.0×10^{4}
Technetium-99	8.0×10^{-1}
Iodine-129	7.5×10^{-5}
Cesium-137	1.7×10^{-4}

a. Source: Picha (1998b, all).

Table A-60. Radioactivity of naval Special-Performance-Assessment-Required waste (curies per package).[a]

Isotope	Short canister	Long canister	Isotope	Short canister	Long canister
Americium-241	5.4×10^{-2}	6.0×10^{-2}	Nickel-59	2.2×10^{2}	2.5×10^{2}
Americium-242m	5.8×10^{-4}	6.5×10^{-4}	Nickel-63	2.7×10^{4}	3.0×10^{4}
Americium-243	5.8×10^{-4}	6.5×10^{-4}	Plutonium-239	2.1×10^{-2}	2.4×10^{-2}
Carbon-14	3.2	3.6	Plutonium-240	5.4×10^{-3}	6.0×10^{-3}
Chlorine-36	5.3×10^{-2}	6.0×10^{-2}	Plutonium-241	4.1	4.6
Curium-242	1.4×10^{-3}	1.5×10^{-3}	Plutonium-242	4.5×10^{-5}	5.1×10^{-5}
Curium-243	6.6×10^{-4}	7.4×10^{-4}	Ruthenium-106	2.1×10^{-1}	2.3×10^{-1}
Curium-244	7.0×10^{-2}	7.9×10^{-2}	Selenium-79	1.2×10^{-5}	1.3×10^{-5}
Curium-245	1.3×10^{-5}	1.5×10^{-5}	Samarium-151	1.7×10^{-2}	1.9×10^{-2}
Cesium-134	1.6	1.8	Tin-126	1.2×10^{-5}	1.3×10^{-5}
Cesium-135	1.1×10^{-5}	1.2×10^{-5}	Strontium-90	4.2×10^{-1}	4.7×10^{-1}
Cesium-137	1.1	1.3	Technetium-99	5.3×10^{-4}	6.0×10^{-4}
Hydrogen-3	1.5	1.7	Uranium-232	1.2×10^{-4}	1.4×10^{-4}
Krypton-85	4.9×10^{-2}	5.6×10^{-2}	Uranium-233	7.8×10^{-5}	8.8×10^{-5}
Niobium-93m	3.6×10^{-1}	4.1×10^{-1}	Zirconium-93	3.8×10^{-1}	4.3×10^{-1}
Niobium-94	5.9×10^{-1}	6.7×10^{-1}			

a. Source: Beckett (1998, Attachment 1).

Table A-61. Typical chemical composition of Special-Performance-Assessment-Required low-level waste.[a]

Source[b]	Composition
Hanford	Vitrified fission products in glass waste form; hot cell waste
INEEL	Activated metal
ORNL	Activated metal; isotope production waste; hot cell waste
WVDP	Activated metal; vitrified transuranic waste
Naval Reactors	Activated metal (zirconium alloy, Inconel, stainless steel)
Other generators	Stainless-steel sealed sources

a. Source: Picha (1998b, all).
b. INEEL = Idaho National Engineering and Environmental Laboratory; ORNL = Oak Ridge National Laboratory; WVDP = West Valley Demonstration Project.

A.2.6.4 Final Waste Form

The final disposal method for DOE Special-Performance-Assessment-Required waste is not known. If the Department disposed of such waste in a repository, it is assumed that the material would be placed in a disposable package before shipment to the repository. The EIS assumes the use of a dual-purpose canister similar to those used for naval fuels for all rail shipments and packages similar to a high-level radioactive waste canister for all truck shipments.

A.2.6.5 Waste Characteristics

The low-level waste from West Valley consists of material in the Head End Cells (5 cubic meters [177 cubic feet]) and remote-handled and contact-handled transuranic waste (545 cubic meters [19,000 cubic feet]). The estimated radioactivity of the material in the Head End Cells is 6,750 curies, while the activity of the remote-handled and contact-handled transuranic waste is not available at present (Picha 1998b, all). The naval Special-Performance-Assessment-Required waste consists primarily of zirconium alloys, Inconel, and stainless steel (Beckett 1998, all); Table A-60 lists the specific radioactivity of the projected material 5 years after discharge.

The specific activity associated with the radium sources at Argonne National Laboratory-East has not been determined. However, in comparison to the other Special-Performance-Assessment-Required waste included in this section, its impact would be small.

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